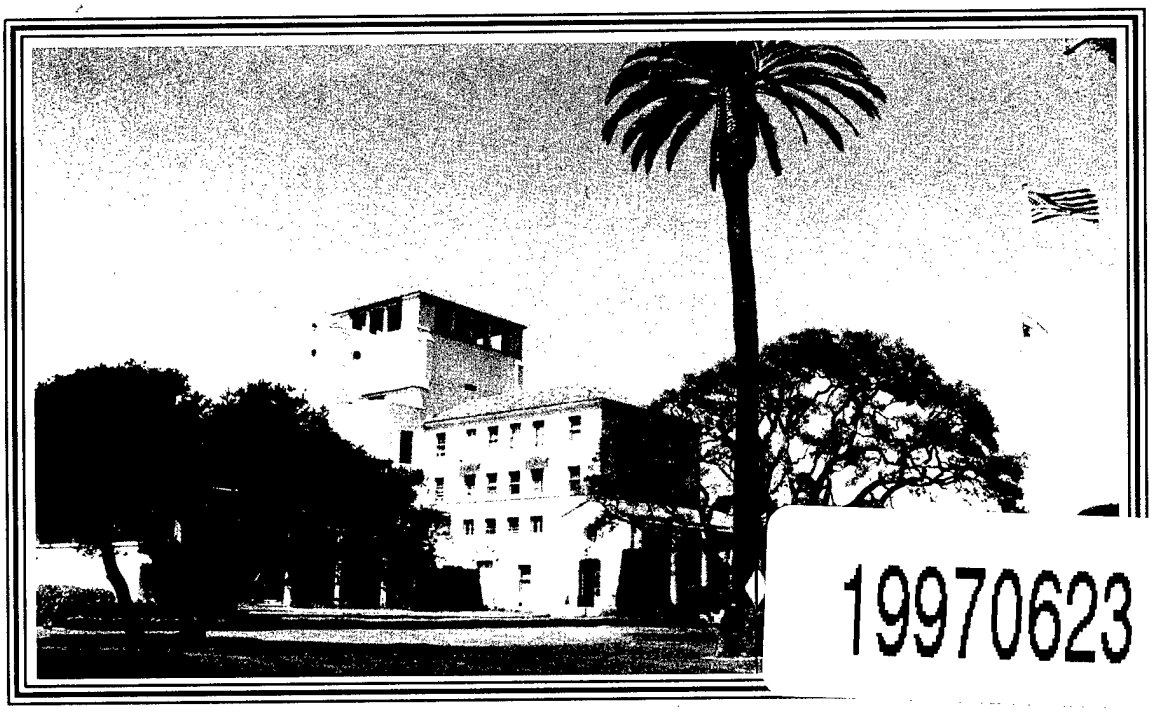
Volume I of II

Proceedings of the

Technology and the Mine Problem Symposium

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18-21 November 1996
Naval Postgraduate School, Monterey, California

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Welcome
to the
Naval Postgraduate School.

Few post-Cold War challenges possess the urgency of the Mine Problem both in military and humanitarian terms. We at NPS are dedicated to the exploration of technical approaches to the solution of the Mine Problem. Your generous participation in this Symposium series underscores the community-wide appreciation of the urgency of this problem. Together, I feel certain we shall meet our objective of "changing the world."

The Faculty, Staff and Students of NPS stand ready to acquaint you further with this very special place. I sincerely hope that, while you are here, you will avail yourselves of the opportunities to get to know us, to see the possibilities in the Technology Transfer Program, and to forge professional networks to deal with the multi-faceted dimensions of the Mine Problem.

Marsha J. Evans
Rear Admiral, United States Navy
Superintendent

Proceedings of the

Technology and the Mine Problem Symposium

Second in the Series of Sesquiannual Symposia

Edited by

Professor Albert M. Bottoms
Ellis A. Johnson Chair of Mine Warfare,
Naval Postgraduate School
Symposium General and Organizing Chair

Barbara Honegger, M.S.
Symposium Program Coordinator
and
Proceedings Editor

Volume I of II

ACKNOWLEDGEMENTS

An enterprise of the magnitude of the Symposium on Technology and the Mine Problem is a coordinated team effort amongst sponsors, speakers, schedulers, Session Chairs, symposium staff, and the attendees. The planning horizon for such a symposium is over one year for staff and presenters alike. On behalf the Mine Warfare Association, I extend thanks and appreciation to the following:

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of the Symposium

MINE LINES and THE MINE WARFARE ASSOCIATION (MINWARA)

The Symposium Announcement and Registration Issues of MINE LINES were sent to an expanded mailing list. This was made possible by planning funds from the Office of Naval Research. The PROCEEDINGS of this Symposium will be mailed in February 1997 to each registrant as part of the Registration Fee.

The Mine Warfare Association (MINWARA) was formed as a Not-for-Profit Corporation in the Commonwealth of Virginia for the purposes of education and communication about Mine Warfare and the Mine Problem. MINWARA derives its support from Corporate and Individual Memberships. There is no subsidy for publication and mailing of MINE LINES. MINWARA lacks the resources to send MINE LINES to the 7,000 or more recipients of the Registration Issue.

MINE LINES is the Newsletter of the Mine Warfare Association. Through MINE LINES we seek to stimulate professional exchange and to announce the periodic workshops and meetings that MINWARA will sponsor and co-host. These events are in addition to the sesquiannual Symposium on Technology and the Mine Problem.

A Membership Application for the Mine Warfare Association is available in this Proceedings. Further information, and information on Corporate Membership classes and benefits, can be obtained from the MINWARA Secretary-Treasurer, Dr. Joseph Molitoris, at (703) 339-7244.

TABLE OF CONTENTS

Volume I of II

PREFACE

Acknowledgements iii
Table of Contents v
Introduction xix
Prof. Albert M. Bottoms
Welcoming Remarks xxvii
CAPT James M. Burin, USN
Sponsors' Remarks xxix
RADM Paul G. Gaffney II, USN; Dr. Fred E. Saalfeld; Dr. David Skinner
Introductory Remarks xxxi
Prof. Albert M. Bottoms

CHAPTER 1: THE CHALLENGE

Keynote Address
GEN John J. Sheehan, USMC 1-1

Technology, the Budget and Politics
ADM Stan Arthur, USN (Ret) 1-35

Technology and the Mine Problem: An Evolutionary Revolution 1-39
Prof. Albert M. Bottoms

CHAPTER 2: OPERATIONAL REQUIREMENTS AND PERSPECTIVES

Introduction 2-1

U.S. Army Initiatives in Mine Warfare 2-3
MGEN Clair F. Gill, USA (Personal Representative of GEN W. Hartzog, USA)

An Entirely New Approach to the Countermine Mission 2-29
COL Robert Greenwalt, Jr., USA

U.S. Air Force Roles in Mine Warfare 2-79
COL Leroy Barnidge, USAF (Personal Representative of LTGEN Phillip E. Ford, USAF)

U.S. Marine Corps Perspectives on Technology and the Mine Problem 2-89
LTGEN Jefferson Davis Howell, Jr., USMC

U.S. Navy Perspectives on the Present and Future of Mine Warfare 2-97
RADM Dennis R. Conley, USN

The Future of the Pacific Fleet 2-119
RADM John F. Sigler, USN

The Joint Mine Countermeasures/Countermine Advanced Concepts Technology Demonstration (ACTD) Process 2-139
Mike Jennings, Doug Todoroff

The Importance of Keeping Historical Records Available in Mine Warfare 2-145
Tamara Melia Smith

Developments in Marine Corps Mine Warfare 2-153
MAJGEN John E. Rhodes, USMC

CHAPTER 3: OPERATIONAL ENVIRONMENTS AND THREATS

Introduction 3-1

Mine Clearance in the Real World 3-3
MAJ Colin King, British Army (Ret)

The Anti-Personnel Mine Threat.....3-11
Harry N. (Hap) Hambric, William C. Schneck

The Proliferation of the Mine Threat and the PRORYV System 3-47
Victor Newton, Terry Kasey

Session on the Littoral Environment at the Monterey Bay Aquarium 3-51

Developments in Rapid Environmental Assessment 3-53
RADM Paul E. Tobin, USN

Developments in the Very Shallow Water - Mine Countermeasures Test Detachment Program 3-57
CAPT Thomas R. Bernitt, USN

CHAPTER 4: LANDMINES AND HUMANITARIAN DEMINING

Introduction 4-1

The History and Future of U.S. Policy on a Universal Anti-Personnel Landmine Ban.....4-5
The Hon. H. Allen Holmes, Assistant Secretary of Defense, SOLIC

Humanitarian Demining and Mine Policy: Chair's Opening Remarks.....4-21
Prof. Fred Mokhtari

An Open Letter to President Clinton.....4-23
Signed and Submitted by LTGEN Robert C. Gard, USA (Ret)

Seeking Real Solutions to the Landmine Problem.....4-25
Robert Sherman, U.S. Arms Control and Disarmament Agency

Banning Anti-Personnel Landmines.....4-27
Stephen D. Goose, Human Rights Watch

Technology and Humanitarian Demining 4-31
Garth Barrett

Bringing New Technology to Bear on Landmine Detection: The Role of NGOs as Catalysts and Liaisons Between Technology Providers and Mine-Affected Countries.....4-35
Richard M. Walden

Research and Development in Support of Humanitarian Demining: Meeting the Landmine Challenge 4-39
Harry M. (Hap) Hambric, Beverly D. Briggs, Thomas L. Henderson

Command Communications Video and Light System (CCVLS) 4-51
Sean Patrick Burke

Cooperation in Europe for Humanitarian Demining 4-57
Prof. J. D. Nicoud

Post-Conflict and Sustainable Humanitarian Demining 4-63
Prof. J. D. Nicoud

Minefield Proofing and Route Clearing in Bosnia Using Unmanned Ground Vehicles and the Standardized Teleoperation System 4-67
David W. Parish, LTC Jon Moneyhun

Multi Sensor Vehicular Mine Detection Testbed for Humanitarian Demining 4-73
Douglas Brown, Joseph Bendahan, Giancarlo Borgonovi, Delmar Haddock, Jason Regnier

Tele-Operated Ordnance Disposal System for Humanitarian Demining 4-79
Jason Regnier, Joseph Foley

Mine Marking and Neutralization Foam.....4-87
Steven Tunick, Jason Regnier

The Development of a Multimedia Electronic Performance Support System
for Humanitarian Demining 4-95
William C. Schneck, Amos (Sam) L. Samuel

LEXFOAM for Humanitarian Demining 4-99
C. John Anderson, Joseph L. Trocino

CHAPTER 5: PROGRESS IN AUTONOMOUS SYSTEMS FOR MINE WARFARE

Introduction 5-1

The Basic UXO Gathering System (BUGS) Program for Unexploded Ordnance
Clearance and Minefield Countermeasures: An Overview and Update.....5-3
Christopher DeBolt, Christopher O'Donnell

Small Autonomous Robotic Technician 5-11
Bryan Koontz, Charles Tung, Ely Wilson

Enabling Techniques for Swarm Coverage Approaches.....5-23
Helen Greiner, Colin Angle, Joseph L. Jones, Art Shectman, Richard Myers

Control of Small Robotic Vehicles in Unexploded Ordnance Clerance 5-37
A. J. Healey, Y. Kim

Unexploded Ordnance Clearance and Minefield Countermeasures
By Multi-Agent, Small Robotics 5-43
Craig Freed, Tuan Nguyen

DARPA's Autonomous Minehunting and Mapping Technologies
(AMMT) Program 5-63
Claude P. Brancart

GPS and Mine Warfare 5-73
James R. Clynch

The *Phoenix* Autonomous Underwater Vehicle 5-79
Don Brutzman, Tony Healey, Dave Marco, Bob McGhee

A Small Co-Axial Robotic Helicopter for Autonomous Minefield Search and Destroy Missions 5-101
Charles Colby

Fully Autonomous Land Vehicle for Mine Countermeasures 5-109
Raymond C. Daigh

Advanced Technology: It's Available at JPL 5-121
James R. Edberg

Mission Planning for an Autonomous Undersea Vehicle: Design and Results 5-125
Michael J. Ricard

An Integrated Ground and Aerial Robot System for UXO/Mine Detection 5-135
Yutaka J. Kanayama, Isaac Kaminer, Xiaoping Yun, Xavier Maruyama, Nelson Ludlow

The Coastal Battlefield Reconnaissance and Analysis (COBRA) Program For Minefield Detection 5-141
Ned H. Witherspoon, Bob Muise, James A. Wright

Clandestine Mine Reconnaissance: Unmanned Undersea Vehicles 5-149
CAPT Charlie B. Young, USN

The *Iguana*: A Mobile Substitute for Landmines 5-179
John Arquilla, Barbara Honegger

Mission Definition for AUVs for War Gas Ammunition Deposit Assessment 5-181
Marek Narewski, Leszek Matuszewski

The Lemmings/BUGS System 5-189
Arnis Mangolds

Application of the Explosive Ordnance Disposal Robotic Work Package to the Clearance of Terrestrial Improved Conventional Munitions (AutoRECORM) 5-191
Gary M. Trimble

CHAPTER 6: COUNTERING MINES ON LAND

Introduction 6-1

Systems and Technologies for Countering Mines on Land 6-3
Col Robert Greenwalt, Jr., USA

GPR and Metal Detector Portable System 6-27
Prof. J. D. Nicoud

Mine Detection with Modern Day Metal Detectors 6-33
Gerhard Vallon

Technology Assessment of Passive Millimeter Wave Imaging Sensor
for Standoff Airborne Mine Detection 6-39
Brad Blume, Sam Taylor, Jack Albers, Ned H. Witherspoon

DARPA's Hyperspectral Mine Detection Program 6-51
C.J. Sayre, D.J. Fields, A.P. Bowman, A.L. Giles, E.M. Winter, F.J. Badik,
M.J. Schlangen, P.G. Lucey, T.J. Williams, J.R. Johnson, J. Hinrichs,
K.A. Horton, G. Allen, A.D. Stocker, A. Oshagan, W. Schaff, W. Kendall,
M.R. Carter, C.L. Bennett, W.D. Aimonetti

On the Feasibility of Microwave Imaging of Buried Landmines at a
Modest Stand-off Distance 6-57
J.T. Nilles, G. Tricoles, G.L. Vance

Chemical Systems for In-Situ Neutralization of Landmines in Peacetime 6-61
Divyakant Patel, Beverly Briggs, Allen Tulis, James Austing, Remon Dihu, Alan Snelson

Radar Imaging Experiments for Landmine Detection 6-67
Stephen G. Azevedo, J.E. Mast, E.T. Rosenbury

Ultra-Wideband, Short Pulse Ground-Penetrating Radar: Theory and Measurement 6-69
Lawrence Carin, Stanislav Vitebskiy, Marc Ressler, Francis Le

Volume II of II

CHAPTER 7: TECHNOLOGIES FOR COUNTERING MINES AT SEA

Introduction 7-1

The Underwater Influence Fields of Target Ships: Some Mine Sensor System Considerations and the Strengths and Weaknesses of Influence Mine Sweeping 7-3
Dennis R. Hiscock, Royal Navy, U.K. (Ret)

Pervasive Technical Issues Related to Organic Mine Countermeasures 7-15
John Richard Benedict, Jr.

Identification of Underwater Mines via Surface Acoustic Signature 7-47
Dale A. Lawrence, Renjeng Su, and Noureddine Kermiche

Advances in the Magnetic Detection and Classification of Sea Mines and Unexploded Ordnance 7-53
Ted R. Clem

Passive Mine Detection 7-67
Charles H. Dabney

Autonomous Detection and Classification of Bottom Objects with Multi-Aspect Sonar... 7-69
Robert W. Floyd, John E. Sigurdson

A Neural Network Approach to the Detection of Buried Objects in Seafloors 7-85
Raj Mittra

Free Surface Slope Signature of Moored Mines in a Current: Experimental Results 7-89
P.M. Smith

Seismo-Acoustic Sonar for Buried Object Detection 7-99
Thomas G. Muir, D. Eric Smith, Preston S. Wilson

Portable Turnkey UXO Detection System..... 7-105
Gerhard Vallon, Okkar Dietz

Rapid Response: A Demonstration of Rapid Environmental Assessment Technologies for Mine Warfare 7-109
William Roderick

SLICE: A Stable Reconfigurable Platform, a New MCM Opportunity 7-113
Steven Loui, Terry Schmidt

Rapid Response Minesweeping 7-123
Carl Fisher

Implications of Single-Point, Mobile-Charge and Distributed Wide-Area Architectures for Mine Warfare 7-125
Walter E. Dence, Jr.

History and Evolution of Minehunting Technology 7-129
Celeste Z. Hansel

MCM Applications of a Virtual Environment-Based Training System for ROV Pilots... 7-137
Barbara Fletcher

Clandestine Reconnaissance in Very Shallow Water with a Mine Reconnaissance Underwater Vehicle 7-145
CAPT Dan Hendrickson, USN (Ret)

The First Mine Countermeasure Devices with Superconducting Magnets 7-183
Vladimir Karasik, Gennady Agapov, George Kurlijandtsev, Vladimir Tsikhon, Vladimir Malginov, Anatoly Rusinov, Valentine Matokhin, Michael Sidorov, Alex Konjukhov, Vitaly Vysotsky

Acoustic Time Series Simulator (ATSS) Synthetic Environment Applied to Mine Warfare..... 7-191
J. W. Kesner

Automated Mine Identification Using Wavelet Analyzing Functions 7-199
Mark E. Lehr, Keh-Shin Lii

Acoustic Characterization of Seagrasses and their Effects on Mine-Hunting Sonars.... 7-209
Elena McCarthy

New Technologies for the Military: Mine Warfare as a Test Case 7-215
Joseph J. Molitoris

D8 Tractor/Israeli Mine Plow (IMP) Mine and Obstacle Clearance Testing 7-233
John P. Wetzel

Reduced Wavenumber Synthetic Aperture for MCM Applications 7-241
Ira Ekhaus

Mine Burial Experiments in Carbonate Sediments 7-253
Daniel F. Lott, Kevin L. Williams, Darrell R. Jackson

Buried Target Image Quality 7-263
Nicholas P. Chotiros

Clutter Sensitivity Test Under Controlled Field Conditions 7-269
Larry Stolarczyk, Joseph M. Mack

Analysis and Time Frequency Processing of Scattered Signals from Submerged Mines in Shallow Water 7-319
Lawrence Carin, Marc McClure

Imaging Small Scatterers in Shallow Water from Towed Array Data 7-321
Meng Xu, Norman Bleistein

Development of a Conductively-Cooled Superconducting Magnet System for Mine Countermeasures 7-323
E. Michael Golda

The Continuous Improvement Process 7-325
RADM Richard D. Williams III, USN, PEO Mine Warfare

CHAPTER 8: ALTERNATIVE APPROACHES TO MINE CLEARANCE, TECHNOLOGIES FOR OBSTACLES AND THE SURF ZONE

Introduction 8-1

Coordination of Department of Defense Efforts for the Disposal of Unexploded Ordnance 8-3
Christopher O'Donnell

Surf Zone Technology: Enabling Operational Maneuver from the Sea 8-13
Daniel A. Crute

Thunder Road: Ballistically Delivered Distributed Explosive Nets 8-21
Donald Robeson, Michael Farinella, Arnis Mangolds

Explosive Neutralization Techniques 8-27
Les Taylor

Pulse Power: 21st Century Platform Defense for Mines and Torpedoes 8-53
RADM Charles F. Horne III, USN (Ret)

Is the Application and Utilization of All the Required Skills Being Applied Within the Mechanical Mine Clearance Arena? 8-57
William N. Baker

Alternative Approaches to Minesweeping and Mine Clearance 8-61
Warren Loughmiller

Application of Seismic Vibration Concepts for Rapid Mine Clearance and Detection....8-65
Geoffrey C. Davis, Steve Ballinger

LCAC Autonomous Algorithms 8-83
Jaime Bunczek

Rigid Polyurethane Foam Technology for Countermine (Sea) Program 8-91
R. L. Woodfin

'MODS' - Mobile Ordnance Disrupter System 8-103
Owen Hofer

In-Stride Mine and Obstacle Breaching for Amphibious Assaults 8-105
Rudy Wiley, Kris Irwin, Tim Hennessey, Phong Nguyen, Eric Scheid

Man-Portable Mine Clearing Line Charge System 8-107
Michael Voisine, A. Jonathan Bawabe

Mine Vulnerability 8-109
Joel Gaspin

Bombs for Clearing 8-111
Ferrell W. Furr, Reid McKeown

Deployment Modeling 8-113
Kennard Watson, Thai Nguyen

CHAPTER 9: THE UNDERLYING SCIENCE OF MINE WARFARE SYSTEMS

Introduction 9-1

Automated Task Division and Group Behavior in Autonomous Robots 9-3
Maja J. Mataric

The Physics of Magnetic Signatures 9-5
Carl S. Schneider

Sensors and Sensory Fusion for Minefield Surveillance and Reconnaissance 9-11
Ruzena Bajcsy, Max Mintz

The Use of Ocean Optical Data to Predict the Performance of Mine Detecting Ocean Lidar Systems 9-49
R. Norris Keeler

The Mechanics and Control of Biomimetic Robotic Locomotion 9-79
Joel Burdick, Bill Goodwine, Jim Ostrowski

CHAPTER 10: SOME ANALYTICAL AND SIMULATION RESULTS

Introduction 10-1

Evaluation of Intelligent Minefields 10-3
John A. Marin, Donald R. Barr

Evaluation of AUV Search Tactics for Rapid Minefield Traversal Using Analytic Simulation and a Virtual World 10-21
Don Brutzman, Bryan Brauns, Paul Fleischman, Tony Lesperance, Brian Roth, Forrest Young

Transition and R&D Recommendations Resulting from the MCM Tactical Environmental Data System (MTEDS) Program 10-35
Samuel G. Tooma, Daniel F. Lott

Littoral Remote Sensing 10-45
Frank L. Herr, CAPT Dennis Ryan, USN, J.M. McDonald

A Network-Centric Information Systems Architecture.....10-47
Rex Buddenberg, LT Steve Graves, USN

Information Warfare and the Countermine Problem 10-57
Edward C. Gough, Jr., Robert L. Barrett

CHAPTER 11: PRESERVING THE MINE/COUNTERMINE EXPERIENCE

Introduction 11-1

Lessons Learned and Operational Experience in Mine Warfare at Sea 11-3
Frank Uhlig, Jr.

Process Challenges and Examples: A Reality Check 11-11
Tamara Melia Smith

NSAP and Operational Experience 11-23
Susan L. Bales, J. Charles Wicke

Mine Countermeasures Exercise Analysis: A Historical Review 11-51
George W. Pollitt

Development History of the Family of Destructors 11-57
Charles A. Rowzee

MIREM Goals and Exercises: Past, Present and Future.....11-73
LCDR Frank Daggett, USN

CHAPTER 12: ACQUISITION AND MARKET STRATEGY ISSUES

Introduction 12-1

Precis of Remarks by Mr. Ed Zdankiewicz, Deputy Assistant Secretary of the Navy for Undersea Warfare 12-3
Prof. Albert M. Bottoms

Identifying and Sizing the Mine Warfare Market: Summary Overview of Roundtable.....12-5
Ric Trotta, with Comments by Ron Blue

APPENDIX A: **A TUTORIAL BRIEF**: The Technological Revolution in the Mine Problem, including Bibliographies on Naval Mines and Landmines.....A-1
Prof. Albert M. Bottoms

APPENDIX A-1: **BIBLIOGRAPHY ON SEA MINES AND COUNTERMEASURES, 1970-1996**.....A1-1
Greta E. Marlatt, Michaele Lee Huygen

APPENDIX A-2: **BIBLIOGRAPHY ON LAND MINES AND DEMINING, 1970-1996**.....A2-1
Michaele Lee Huygen, Greta E. Marlatt

APPENDIX A-3: **BIBLIOGRAPHY ON MINE WARFARE**.....A3-1
Richard Hansen

APPENDIX B: **1996 SYMPOSIUM SPEAKERS AND ATTENDEES**.....B-1
(Names and contact information)

APPENDIX C: **MINE WARFARE ASSOCIATION INFORMATION AND MEMBERSHIP APPLICATION**.....C-1

APPENDIX D: **INTERNET SITES**.....D-1
<http://www.minwara.org>
<http://www.demining.brtrc.com>

STANDARD FORM 298.....Final Page

INTRODUCTION

Professor Albert M. Bottoms
Naval Postgraduate School

This volume contains the PROCEEDINGS and contributed papers of the Second Symposium on Technology and the Mine Problem, held at the Naval Postgraduate School November 18-21, 1996. The First Symposium, entitled Symposium on Autonomous Vehicles in Mine Countermeasures, was held at the School in April 1995.

This Second Symposium was dedicated to the memory of Admiral Jeremy "Mike" Boorda, USN, the former Chief of Naval Operations, who was a staunch supporter of efforts to harness technology to deal with the Mine Problem.

The Honorary Chair of this Second Symposium was Rear Admiral John D. Pearson, USN, the outgoing Commander of the U.S. Navy Mine Warfare Command.

The Organizing and General Chair of the Symposium was Albert M. Bottoms, Ellis A. Johnson Chair of Mine Warfare at the Naval Postgraduate School and President of the Mine Warfare Association.

VISION STATEMENT

The vision for evolving mine countermeasures/countermine systems is that of a family or families of affordable, autonomous systems capable of carrying out the tasks associated with the management of risks from mines in the military contexts or clearance assurance in the humanitarian de-mining context. In practice, autonomy will likely be a matter of degree -- progressing from tethered, to remotely operated, to programmed and, finally, to rule-based autonomy. This vision includes the idea of the autonomous mine countermeasures brigade and also recognizes that components of the total system may range in size from bulldozers to automated lobsters. There will be variation in the cost of individual elements depending on size and complexity of the element.

THE CHALLENGE

The Challenge is to solve the Mine Problem.

Apply emerging technologies to create a system or systems costing in the neighborhood of $5,000 in production lots of 100,000. Members of this family of systems must be capable of being operated and maintained by military field units and/or by indigenous personnel in third world countries.

GOALS FOR THE 1996 SYMPOSIUM ON TECHNOLOGY AND THE MINE PROBLEM

* Identify the technologies that can revolutionize approaches to dealing with the mine problem;

* Emphasize those technologies which contribute to the Navy-Marine Corps Mine Warfare Campaign Plan and its thrusts to support Operational Maneuver from the Sea and "organic" mine countermeasures;

* Match technologies and systems with the realities of Humanitarian De-Mining;

* Define the scope, magnitude, and future course of the national and international markets for mine clearance-related technologies and systems, including those based on commercial off-the-shelf (COTS) technology and products.

THE SYMPOSIUM SERIES ON TECHNOLOGY AND THE MINE PROBLEM

In consonance with the objective of establishing the Naval Postgraduate School as a focal point for mine-related technology and analysis, it is the intent to hold a major technical Symposium at the Naval Postgraduate School at intervals of 18 months. The next Symposium will be the week of April 5, 1998, and will emphasize progress in the development of autonomous systems for mine countermeasures/countermine applications, C4I, including tactical decision aids and distributed modeling and simulation; and progress toward breaching -- overcoming obstacles in the surf zone, on the beach, and inland. Each of these major subject areas will be viewed from the standpoint of applications to military mine warfare on land and at sea and to humanitarian demining.

RECOGNITION OF SYMPOSIUM CHAIRS

General and Organizing Chair: Professor Albert M. Bottoms, Ellis A. Johnson Chair of Mine Warfare, Naval Postgraduate School

Honorary Chair: RADM John D. Pearson, USN (Ret), former COMINEWARCOM

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Session X:	Chair, Prof. Fred Mokhtari, Norwich University Co-Chairs, Dr. Jackson E. Ramsey, James Madison University; and Assoc. Prof. Mitch Brown, Naval Postgraduate School

RECOGNITION OF SYMPOSIUM CHAIRS (continued)

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Co-Chair, Assoc. Prof. Mitch Brown, Naval Postgraduate School

Session XIII: Chair, Prof. Anthony ("Tony") Healey, Naval Postgraduate School
Co-Chair, Dr. Claude Brancart, C.S. Draper Laboratories

Session XV: Chair, Dr. David Heberlein, Program Mgr., Countermine, Fort Belvoir
Co-Chair, COL Robert Greenwalt, USA, Director, Combat Developments, U.S. Army Engineer Center

Session XVI: Chair, Frank Uhlig, Naval War College
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Session XVII: Chair, Ric Trotta, President, Trotta Associates
Co-Chair, Dr. Kevin Owen, Naval Postgraduate School

Session XIX: Chair, RADM Richard D. Williams III, USN, PEO Mine Warfare
Co-Chairs, George Pollitt, Technical Director, COMINEWARCOM, and Assoc. Prof. Don Walters, Naval Postgraduate School

Session XX: Chair, Lee Hunt, former Exec. Dir., Naval Studies Board, National Academy of Sciences
Co-Chair, Asst. Prof. Knox Millsaps, Naval Postgraduate School

Session XXI: Chair, Dr. Ray Widmayer, Technical Director, Mine Countermeasures, Expeditionary Warfare Dir., Office of the Chief of Naval Operations
Co-Chairs, Dennis Hiscock, Former Head, Mine Countermeasures, Royal Navy; Prof. Xavier Maruyama, Naval Postgraduate School

Session XXII: Chair, Prof. J.D. Nicoud, Laboratoire de Micro-Informatique
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Co-Chair, Dennis Hiscock, Former Head, Mine Countermeasures, Royal Navy; Prof. Xavier Maruyama, Naval Postgraduate School

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Co-Chair, Mr. Claude Brancart, C.S. Draper Laboratories

Session XXX: Chair, Dr. Norris Keeler, Kaman Diversified Technologies Corp., and former Director of Navy Technology, Naval Material Command
Co-Chair, Dean and Prof. David Netzer, Naval Postgraduate School

RECOGNITION OF TECHNICAL CONTRIBUTED PAPERS

The Mine Warfare Association established two prize categories for contributed technical papers, first presented at this 1996 Symposium on Technology and the Mine Problem. The CAPTAIN SIMON PETER FULLINWIDER Awards are for the best papers submitted by serving members of the Armed Forces. The First Prize in this category will carry an honorarium of $500 and a Life Membership in the Mine Warfare Association. The Second and Third Prizes will, respectively, carry honoraria of $250 and $100. Each will also be accompanied by Life Membership in the Mine Warfare Association.

Captain Simon Peter Fullinwider (1871-1957) is deemed the Father of Mine Warfare by the U.S. Navy. Additional information about the contributions and energy of this remarkable man can be found in Dr. Greg Hartmann's book Weapons That Wait. This year the award was presented by RADM John D. Pearson, USN (Ret), Honorary Chair of the 1996 Symposium.

The Charles Rowzee Awards are for the best overall technical papers. The schedule of awards is the same as that for the Fullinwider Awards.

Charles Rowzee is the individual who applied years of experience in mine design to, in effect, enable the conversion of the large stocks of bombs into influence mines. This technical achievement led to the mining campaign against North Vietnam. That campaign, in turn, led to the return of the North Vietnamese to the negotiating table and to the subsequent release of Americans held captive by North Vietnam. The 1996 Rowzee Awards were presented by Mr. Charles Rowzee himself.

Dr. Ellis A. Johnson, Captain Simon Peter Fullinwider and Mr. Charles Rowzee are but three of the intellectual and operational giants to whom the United States owes its distinguished accomplishments in the fields of Mine Warfare. There are many others, both in and out of uniform. Perhaps a long-term project for the Mine Warfare community could be the creation of a Mine Warfare Hall of Fame.

The Award recipients for this Second Symposium on Technology and the Mine Problem are:

The 1996 Fullinwider Awards

First Prize
Col. Robert Greenwalt, Jr., USA
The Engineer Center, Ft. Leonard Wood, MO
"Systems and Techniques for Countering Mines on Land"
Col. Greenwalt's papers appear in Chapters 2 and 6

Second Prize
Lt. Col. Dennis Verzera, USMC
Coastal Systems Station, Panama City, FL
"A New Dimension in Amphibious Warfare"
Lt. Col. Verzera's paper appears in Chapter 7

The 1996 Fullinwider Awards (continued)

Third Prize
Capt. Charles Young, USN
U.S. Navy Unmanned Undersea Vehicles Program Office
"Clandestine Mine Reconnaissance, Unmanned Undersea Vehicles"
Capt. Young's paper is in Chapter 5

Honorable Mention
Col. Leroy Barnidge, USAF
Commander, 28th Bombardment Wing, Ellsworth AF Base
"U. S. Air Force Roles in Mine Warfare"
Col. Barnidge's paper is in Chapter 2

Group Awards
Don Brutzman, Bryan Brauns, Paul Fleischman, Tony Lesperance, Brian Roth and Forrest Young, Undersea Warfare Academic Group, NPS
"Evaluation of AUV Search Tactics for Rapid Minefield Traversal Using Analytic Simulation and a Virtual World"
Their paper is in Chapter 10

Group Awards
Capt. Thomas R. Bernitt, USN, Commander, Explosive Ordnance Disposal Group One; CWO G. Mike Johnson, USN; Senior Chief Petty Officer Chris A. Wynn, USN; and Lt. Eric Basu, USN
"Developments in the Very Shallow Water Mine Countermeasures Test Detachment Program"
Their paper is in Chapter 3

The 1996 Rowzee Awards

First Prize
Prof. Carl Schneider, Ph.D
Professor of Physics, U.S. Naval Academy
"Maxwell's Equations in Magnetic Signature Analysis"
Prof. Schneider's paper is in Chapter 9

Second Prize
Major Colin King, Royal Army (Ret.)
Jane's Information Group
"Landmines and Humanitarian DeMining"
Major King's paper is in Chapter 3

The 1996 Rowzee Awards (continued)

Third Prize
Ms. Helen Greiner
ISR Robotics, Inc.
"Enabling Technologies for Swarm Coverage Approaches"
Ms. Greiner's paper is in Chapter 5

Honorable Mentions

Prof. Joel Burdick, Ph.D.
Department of Mechanical Engineering
California Institute of Technology
"The Mechanics and Control of Robotic Locomotion"
Prof. Burdick's paper is in Chapter 9

Profs. Dale Lawrence, Renjeng Su, and Noureddine Kermiche
Center for Space Construction, University of Colorado
"Identification of Underwater Mines Via Acoustic Signature"
Prof. Su's paper is in Chapter 7

Mr. Dennis R. Hiscock, Royal Navy Scientific Service (Ret.)
"The Underwater Influence Fields of Target Ships and
Systems Considerations"
Mr. Hiscock's paper is in Chapter 7

Prof. J. D. Nicoud, Ph.D.
Laboratoire de Micro-Informatique EPFL
Lausanne, Switzerland
"GPR and Metal Detector Portable Systems," "Post-conflict and Sustainable Humanitarian Demining," and "Cooperation in Europe for Humanitarian Demining"
Prof. Nicoud's papers are in Chapters 4 and 6

Mr. Jason Regnier
U.S. Army Night Vision and Electro-Optical Laboratory, Fort Belvoir, VA
"Tele-Operated Ordnance Disposal Systems for Humanitarian Demining"
Mr. Regnier's paper is in Chapter 4

John Richard Benedict, Jr.
The Johns Hopkins University, Applied Physics Laboratory (JHU/APL)
"Pervasive Technical Issues Related to Organic Mine Countermeasures (MCM)"
Mr. Benedict's paper is in Chapter 7

Remarks of
Mr. Charles A. Rowzee

To have an award bear my name is truly an honor and one of the highlights of my career -- especially an award in recognition of solving Mine Problems.

I have always considered myself fortunate to have contributed to solutions of mining problems. For me, this was a satisfying environment.

Before proceeding with the award presentations to the winning participants, let me say a few words about a weapon whose development is the reason why I'm here tongiht. This weapon development was responsible for resolving a difficult sea problem -- the interdiction of roads and inland waterways. I am refering to the Destructor Weapon. This weapon system, consisting of an armful of components, converts the MK-80 series bomb into an underwater or land mine. Development from concept to deployment was accomplished in ten months, providing the Fleet with a safe, effective weapon at a cost of less than a pound of hamburger per pound of weapon.

If you think that this is the complete story, don't believe it. Now let me tell you the "rest of the story." Very simply, it's the Navy Laboratories, where individuals gain knowledge and experience to resolve challenging problems. This major weapon development -- concept to deployment in record time -- could have only been achieved through the years of experience I gained at the Navy Laboratory in White Oak, Maryland. So I say, "Thumbs Up" for the Navy and Defense Labs.

WELCOMING REMARKS

CAPT James M. Burin, USN
Acting Superintendent
Naval Postgraduate School

Good morning. First of all, let me welcome you to the Naval Postgraduate School and Monterey. You have assembled an impressive group and you are meeting on a critical topic.

We have a lot of expertise and technology research here at NPS in mine warfare and related fields, so it's an ideal setting for your conference. While you're here, please feel free to talk to NPS staff and students and see what's going on here in these vital areas.

Since I have the opportunity, I would like to give you a brief on mine warfare. I have dropped some mines, both on land and at sea, and have some mine warfare experience. I have noticed that mine warfare, like nuclear weapons, used to be in war games. But no longer; no one wants to play because these weapons are a real 'show stopper.' Hopefully, you can fix that, so that mines are no longer show stoppers.

I am somewhat of a mine warfare cult figure. As Airwing Commander during Desert Storm, I went into Ash Shuwake Harbor in Kuwait three nights in a row looking for a ship called a Spasilac -- the Iraqi mine laying ship. On the first two trips, all I got was shot at a lot, but no ship. Yet persistence paid off. The third time it was not hidden well enough and I put two laser guided bombs into it. Now, *that*'s a form of mine warfare!

And that leads to my final point. We need to think about mine warfare as a full spectrum problem, like we did about regimental backfire raids on Navy battle groups. Cruise missiles were another tough problem, like mines. So we tried to kill the archer, not the arrow. Then we went beyond air-to-air warfare, where we didn't just kill the arrow and the archer, but the quiver -- we used strike warfare. That should become a part of mine warfare, too. Get our strike warriors to find mines and kill them on the beach. We need to use our full spectrum warfare capabilities and technology to attack this difficult problem.

Again, welcome to the Naval Postgraduate School. I hope and trust you will have a valuable and productive conference.

SPONSOR'S REMARKS

RADM Paul G. Gaffney II, USN
Chief of Naval Research
and
Dr. Fred E. Saalfeld
Deputy Chief of Naval Research, Technical Director

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

IN REPLY REFER TO

5 November 1996

Dear Colleague:

The Office of Naval Research is proud to co-sponsor the 1996 Symposium on Technology and the Mine System, particularly as we celebrate 50 years of bringing science and technology to our Navy and Marine Corps and our Nation.

Welcome to what promises to be an exciting and rewarding week set in the historic and beautiful Monterey Peninsula. We have much to look forward to this week, and the tasks we hope to accomplish are ambitious:

- Identify technologies that can revolutionize approaches to dealing with the mine problem;

- Match technologies and systems with the realities of requirements for Humanitarian De-Mining;

- Define the scope, magnitude, and future course of the national and international markets for mine clearance-related technologies and systems, including those based on commercial, off-the-shelf products and technologies.

We encourage you to take an active role in the symposium -- participate, ask questions, and contribute your ideas. While you are at the symposium please visit the Office of Naval Research exhibit and pick up literature on some of our mine warfare efforts underway.

PAUL G. GAFFNEY, II
Rear Admiral, USN
Chief of Naval Research

DR. FRED E. SAALFELD
Deputy Chief of Naval Research
Technical Director

SPONSOR'S REMARKS

Dr. David Skinner
Executive Director
Coastal Systems Station, Dahlgren Division

DEPARTMENT OF THE NAVY
COASTAL SYSTEMS STATION DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER
6703 WEST HIGHWAY 98
PANAMA CITY FL 32407-7001

Over the course of the past year we have made great strides in the improvement of Mine Warfare (MIW). The NSIA, ADPA, and now the Mine Warfare Association Conference have succeeded in educating and involving industry and academia to a high degree.

The Campaign Plan has provided a rallying point for the future direction of MIW and the Navy is taking notice. Readiness has been improved through the forward basing of MCM-1 ships and the development of contingency systems like RMS and Magic Lantern. Development programs have been streamlined and integration improved from 6.1 through 6.5. Management coordination and interaction have been improved throughout the MIW community through forums like the Flag Off-sites, the Acquisition Coordination Team, and MIW Technology Team.

The near-term goals have been accomplished. The mid-term is closing in and we are on track, but the MIW problem is far from solved. Our vision for the far-term must now be crystallized. The road ahead is sure to be as full of changes as the recent past. The Navy and the DOD are still evolving roles, missions, and functions. As we strive to keep pace with this evolution, several things are clear:

We must become fully integrated into the Naval consciousness;

We must continue to improve the Fleet's MIW capabilities;

We must stay ahead of our adversaries capabilities;

We must be cost effective; and

We must maintain a high level of awareness through the Navy.

How, then, do we solidify this far-term vision? We have already started down the path. We are establishing a common language for analytical discussion of MIW, and we are quantitatively baselining our near and mid-term capabilities with sophisticated modeling and simulation capabilities and Fleet exercises. We must then:

Determine our far-term needs;

Assess our expected capabilities against these needs to determine if we have shortfalls;

Develop approaches to fill these shortfalls;

Program, restructure, and adjust as required to provide the Naval MIW capabilities.

INTRODUCTORY REMARKS

Professor Albert M. Bottoms
Symposium General Chair and
President, Mine Warfare Association

General Sheehan, General Howell, General Gill, Admiral Conley, Admiral Pearson, Admiral Gaffney, Dr. Saalfeld, distinguished guests and attendees:

It gives me great pleasure to open this second in the planned series of major technical Symposia at the Naval Postgraduate School on Technology and the Mine Problem. We plan to hold these every 18 months. The next one is scheduled for April 1998.

The seriousness and urgency of the mine problem can scarcely be overstated. Each person here has interest in and responsibility for some facet of the problem of mines -- operational, technical, programmatic, or policy. These concerns apply to sea mines, land mines, and to humanitarian demining. We note that technologies that relate to mines and mine countermeasures also apply to the efforts to remediate areas contaminated with UXOs or hazardous materials. Mine technology and countermine processes may also be applicable in counter-terrorism.

This week Monterey is the mine capital of the world. We at the Naval Postgraduate School have a vision as to how the emergent technologies about which you will hear eventually will be combined into affordable, autonomous systems that can deal effectively and in a timely manner with mines, booby traps and obstacles. This is precisely what we mean when we say that our objective is "to change the world."

The military art of mine countermeasures is supported by a "System of Systems" -- a tool box of hardware and approaches. We challenge the systems people to think about how and when the emergent technologies can be brought together into systems approaches. Systems people are a breed apart. They see combinations. They intuitively understand mission needs and operational constraints. This Symposium should provide an opportunity for the systems people and the technologists to form networks.

Systems people, along with programmatic sponsors, also think in terms of milestones and time lines. You will hear about the ACTD candidate technologies. The ACTD field exercises in FY'97 and FY '98 are the next official milestone events. But much of what you will hear falls on either side of these ACTD milestones.

Some ideas, such as bulldozers and rakes, may be described as "low tech," but, as Mr. Bill Baker points out, also "high technique." Other ideas involve computational power and

flexibility only now coming within grasp. We urge you to help us identify these post-ACTD milestones. Help us to define for the mine warfare System of Systems the initiatives that correspond to "planning wedges" and "block upgrades" for platform acquisitions.

Now, I ask that we pause in our anticipation of the program over the next four days to honor the memory of Admiral "Mike" Boorda, USN, former Chief of Naval Operations, who personally encouraged our efforts and our vision for mine countermeasures systems at NPS. He wrote that he concurred that the vision is within grasp.

I now call upon the NPS Command Chaplain, Chaplain John Wright, to give the invocation for the Symposium.

CHAPTER 1: THE CHALLENGE

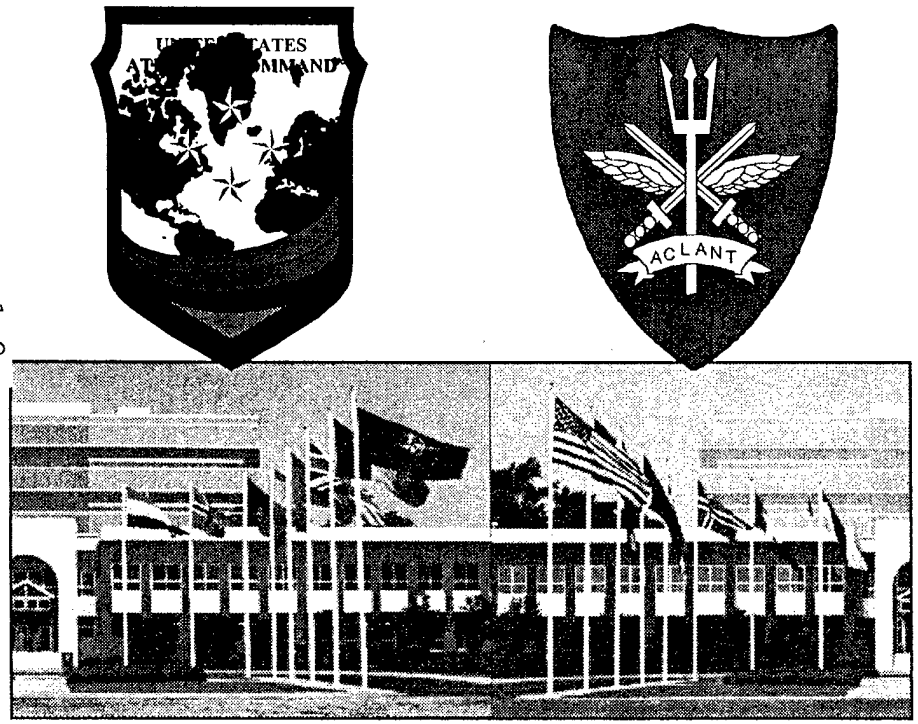
KEYNOTE ADDRESS

GEN John J. Sheehan, USMC
Supreme Allied Commander, Atlantic
Commander, U.S. Atlantic Command

Key Points:

The General's remarks underscored the current inadequacy of U.S. military mine countermeasures, both at sea and ashore, and forecast the likely continuation of the mine problem if money and resources do not match rhetoric.

Presented herein with General Sheehan's express permission are the visuals that he used in his presentation. He spoke without notes.



Confronting the Mine Warfare Challenge of the 21st Century

a presentation to the

NPS Mine Warfare Symposium

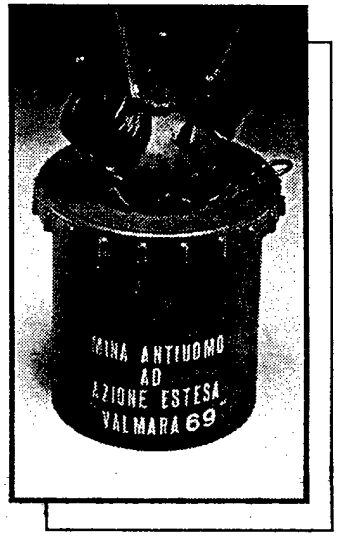
by

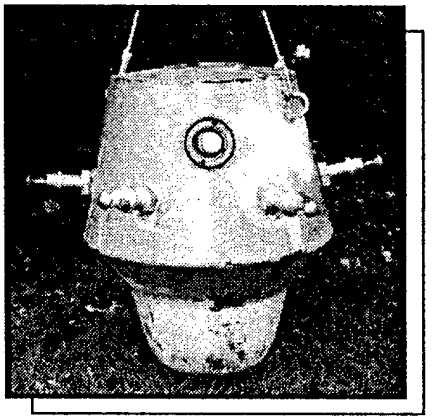
General John J. Sheehan

18 November 1996

Outline

- Asymmetrical Warfare
- Mine Warfare Threat
- Since Desert Storm...
- MCM ACTD: A Joint Response
- Challenges



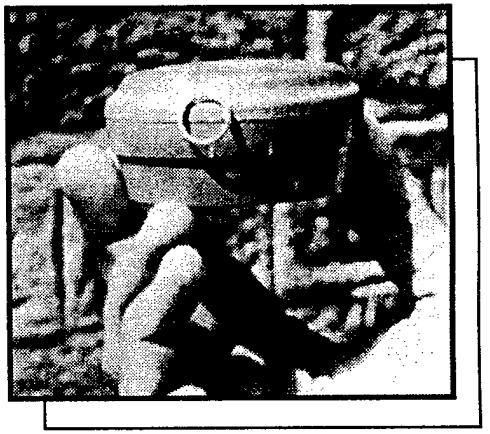


21st Century Military Forces

-- An Asymmetrical Battlefield--

- **Ground**
  - **Rapid Reaction Forces**
  - **Lighter Armor**
  - **Precision Munitions**
  - **Digitized Comms**
  - **Combat Identification**
- **Air**
  - **Multi-Role**
  - **Stealth Technology**
  - **Precision Munitions**
  - **Day-Night**
  - **UAVs/RPVs**
- **Naval**
  - **Expeditionary Forces**
  - **Green/Brown Water Vessels**
  - **Cruise Missiles**
  - **Diesel Submarines**
  - **Mine Warfare**
- **Air Defense**
  - **Multi-Purpose**
  - **Relatively Cheap**
  - **High Quality**
  - **Highly Mobile**
  - **Night Capable**

Asymmetrical Warfare
--The Mine Threat--



- **Serves as a Force Equalizer**
- **Low Cost Weapon System**
- **Deniability**
- **Negates U.S. Technological Advantages**
- **Can Inflict Unacceptable Number of Casualties**



Wonsan, Korea - 1950

We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the time of the birth of Christ.

--CATF's Letter to CNO

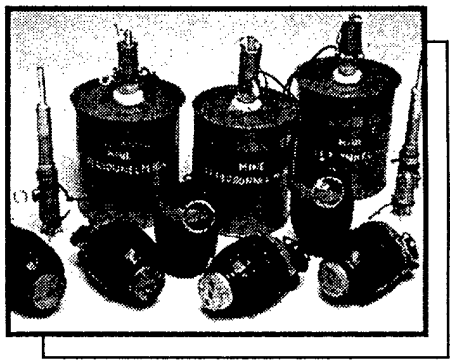
CNO's Assessment

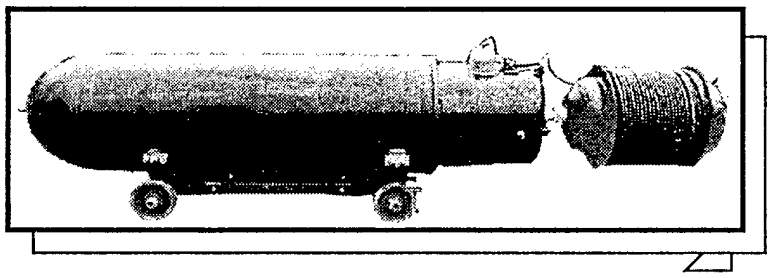
The mining of Wonsan "caught us with our pants down. When you can't go *where* you want to, *when* you want to, you haven't got command of the sea."

--Admiral Sherman, CNO

Since Desert Storm...

- UNPROFOR in Bosnia
- NATO's IFOR Experience
- Global Humanitarian Demining
- Navy/Marine MCM Architecture
- Joint Countermine ACTD





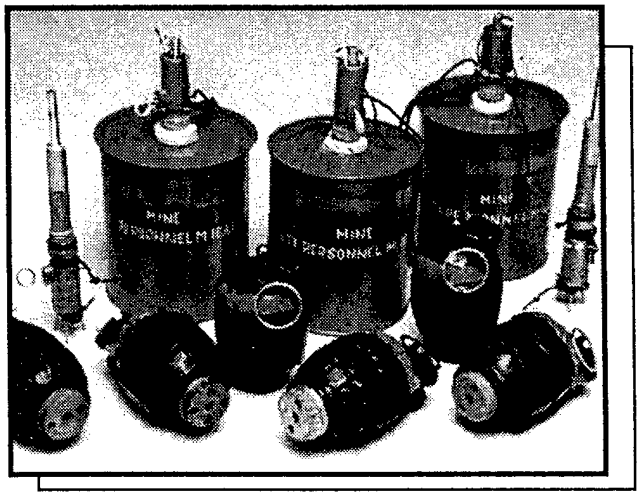
UNPROFOR Experience in Bosnia

--Land Mine Incidents--

174 Incidents resulting in:

- 204 Casualties

- 20 Deaths



Source: GAO

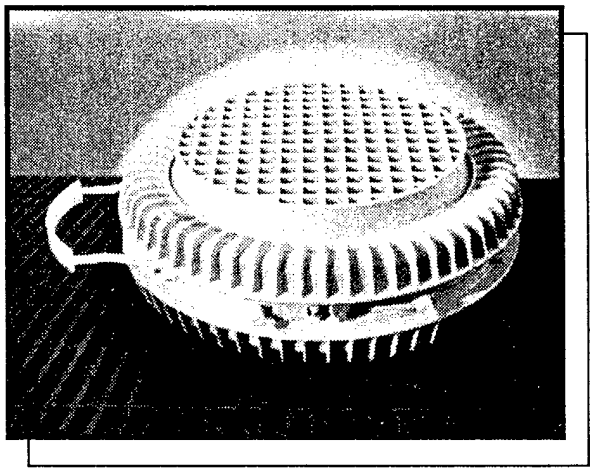
IFOR Experience In Bosnia

--Land Mine Incidents--

Numerous Incidents resulting in:

- **55 Casualties**
- **9 Deaths**





Source: SHAPE Crisis Center

Advanced Concept and Technology Demonstrations (ACTD)

FY95

- ☑ Synthetic Theater of War
- ☑ Advanced Joint Planning
- ☑ Joint Countermine (JCM)
- ☑ High Altitude UAV
- ☑ Medium Altitude UAV

☑ = *Formally accepted*

FY96

- ☑ Battlefield Awareness and Data Dissemination
- ☑ Navigation Warfare
- ☑ Semi-Automated IMINT Processing
- ☑ Combat Identification
- ☑ Logistics (Total Asset Visibility
- ☐ Military Operations in Urban Terrain

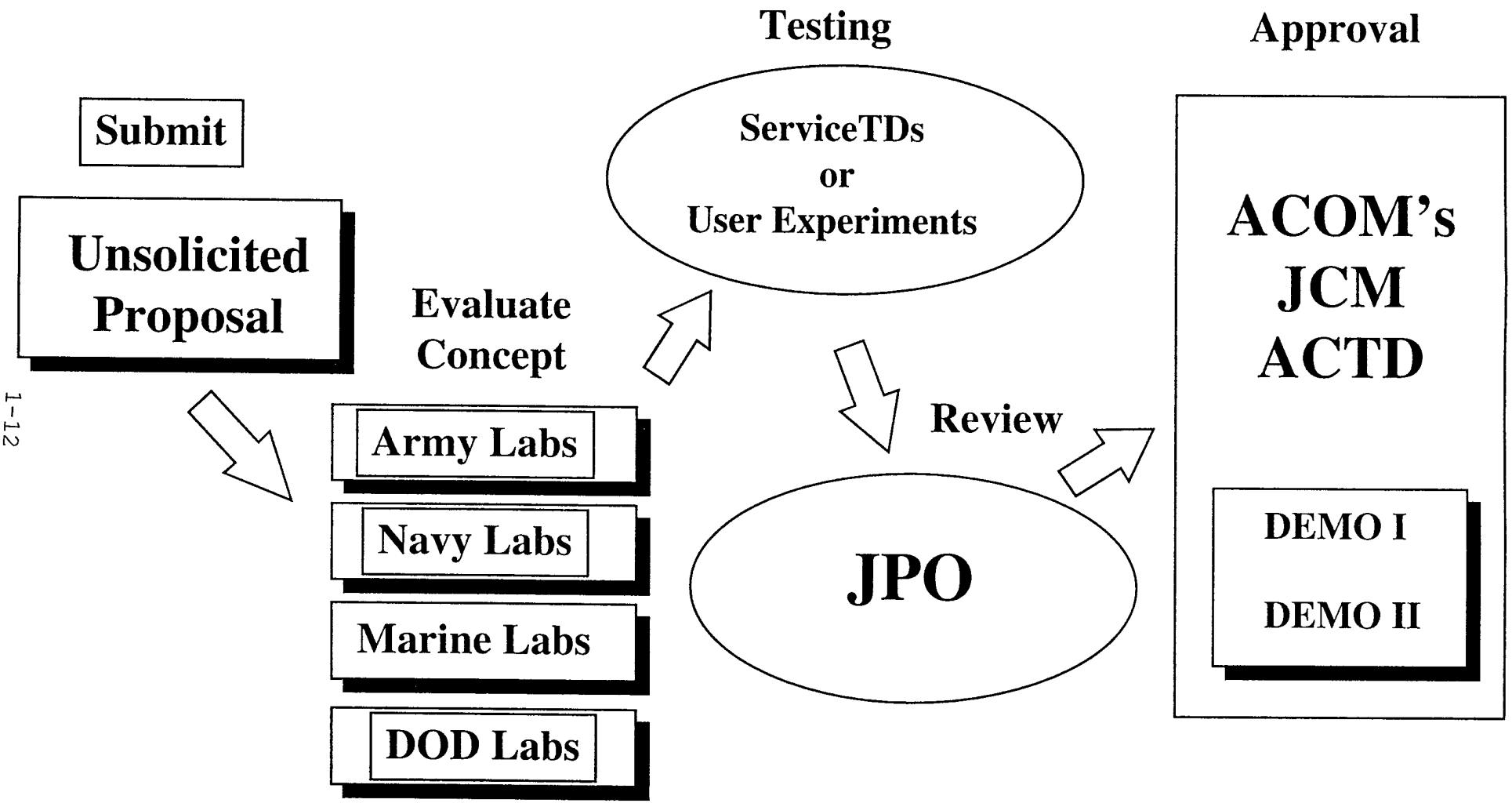
(Formally MOBA) (Moved to FY 97)

ESTIMATED TOTAL USACOM ACTD FUNDING FY95 - FY00: $2.08B+

"Speeding technology to the warfighter..."

Allied Command Atlantic
United States Atlantic Command

JCM ACTD Filtering Process



Allied Command Atlantic
United States Atlantic Command

USACOM's JCM Emphasis

- **Can We Find Mines and Minefields?**
  - Individual System and Combined Effectiveness
  - Improvement Over Current Operational Capability
  - Better Intelligence Collection and Dissemination
- **C4I**
  - GCCS
  - Joint Interoperability
  - Compatible
- **Modeling and Simulation**
  - Credible Training Tool, 100 STOW
  - Will Become Reliable Planning Tool For COA Evaluation

Joint Countermine ACTD

- Initiated 1995
- Demo I (Approved)
  - JTFEX 97-3 (11-29 AUG 97)
  - Assess Services' MCM Capabilities in Realistic Scenario
- Demo II (Proposed) JTFEX 98-2

Joint Countermine ACTD

--Where we need to go?--

<u>Transition IPT</u>: Transfer data collected during the ACTD to the Operational Test and Evaluation Commands for production decisions and approval.

- **<u>Allied/UK Participation</u>: Integration of US. and Allied technology into operational requirements.**

- **<u>Demo III</u>: Look at the CM role in Bosnia type scenario and improvements to residuals systems.**

NATO's MCM Resources

- NATO's MCM Capabilities
- SACLANT Technical Center
- IFOR Lessons Learned
- SHAPE Technical Center

Cooperative Telos

--Corpus Christi, TX,18-29 Sept 97--

Partnership for Peace MCM Exercise

- **1st PfP MCM exercise in CONUS**
- **MCM Wargame**
- **4-day live-ex on board the Inchon**

Challenges

- MCM Technology Remains Suspect
- Mine Threat Still Underestimated
- Funding Pressures on MCM
  - Research and Development
  - Procurement Dollars

Impediments to Progress

- Technological
- Psychological
- Budgetary
- Cultural

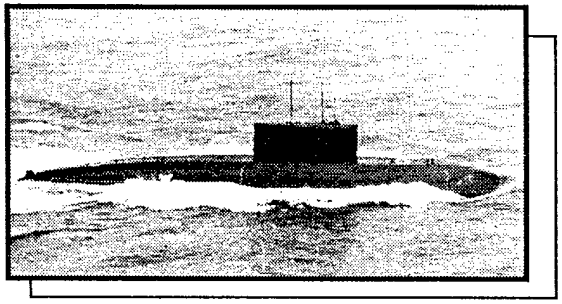
Selective Concern

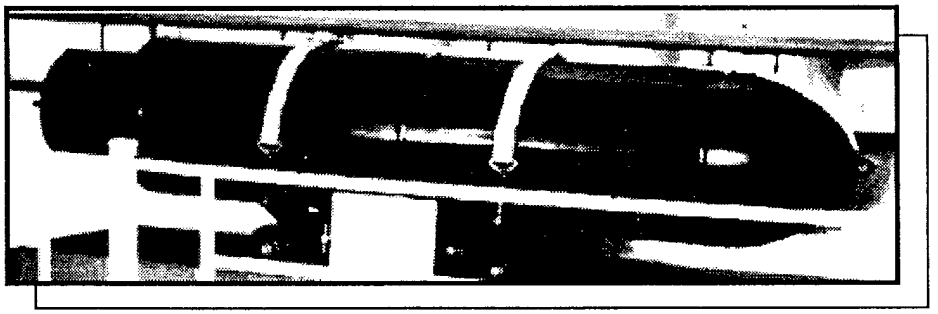
Iranian Diesel Submarine Threat

- Reality: Limited Capability
- Response: General Quarters

Iranian Mine Threat

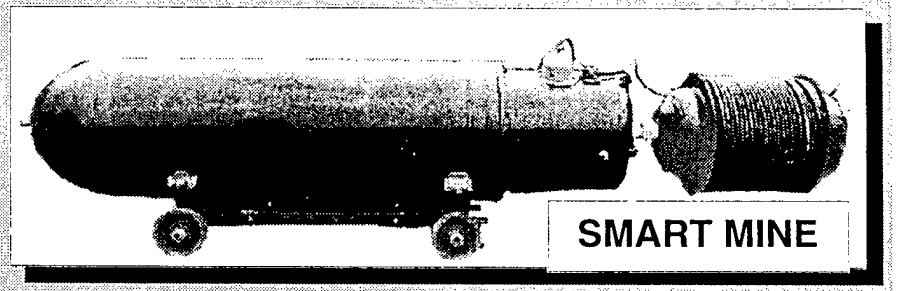
- Reality: Proven Capability and Extensive Inventory
- Response: Limited Concern





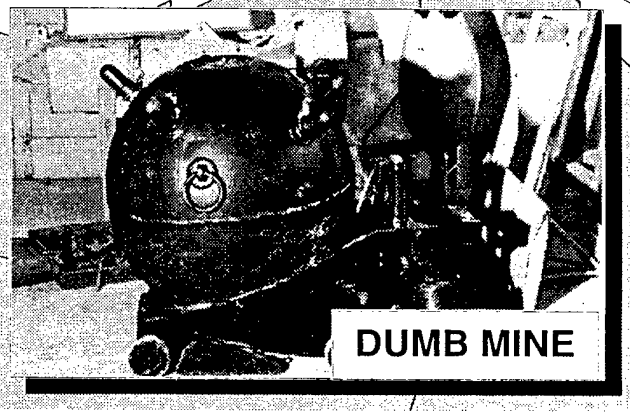
PERSIAN GULF

100 FT



200 FT

300 FT



- DEPTH S < 300FT
  VULNERABLE TO MINING

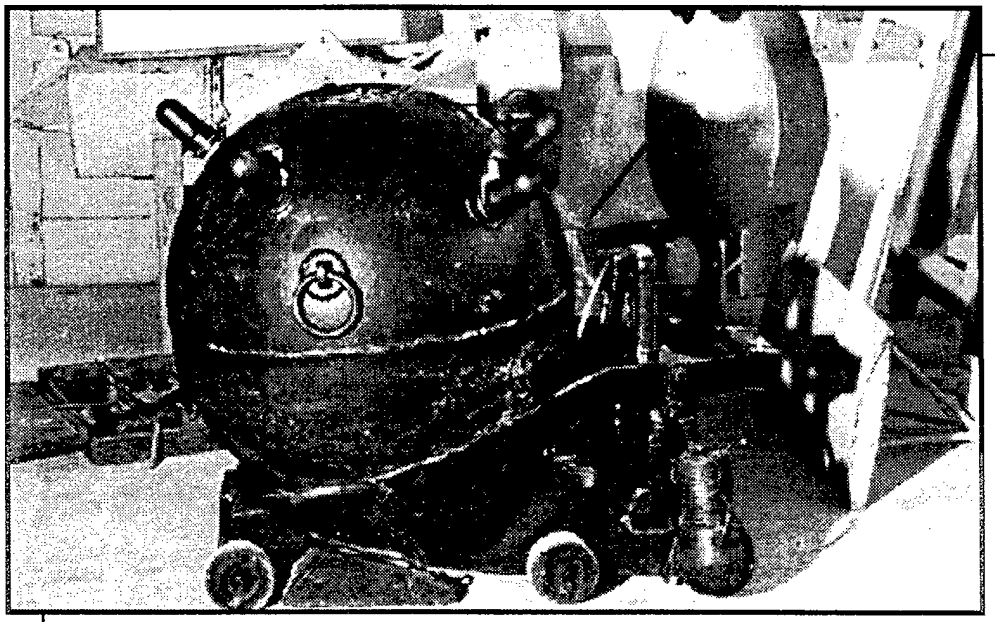
Allied Command Atlantic
United States Atlantic Command

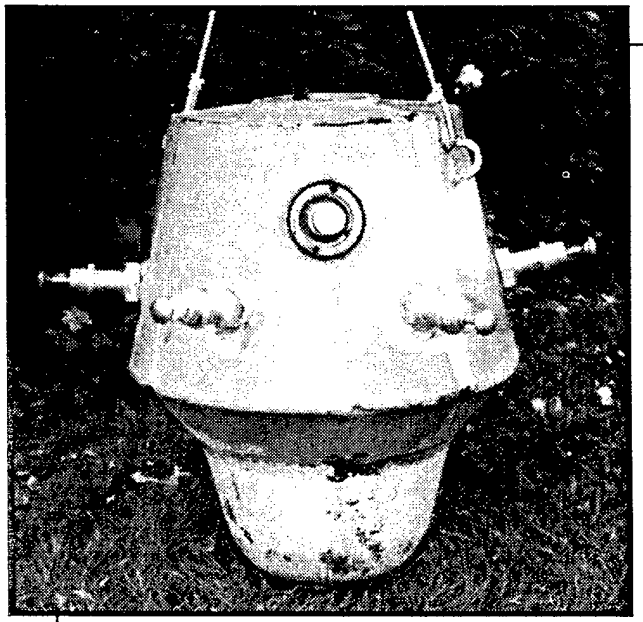
What is Undersea Warfare?

- **1 V 1 ?**
- **Wolfpacks of Kilo/Type 209s?**
- **Dumb Mines?**
- **Smart Mines?**

MINE WARFARE

DUMB MINES

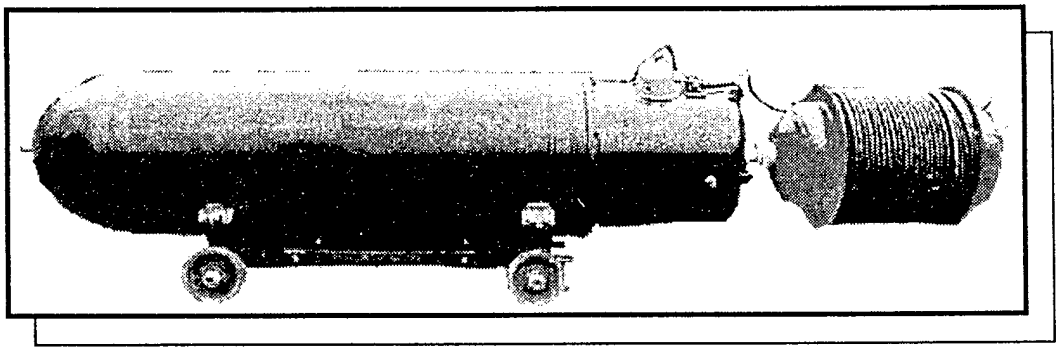




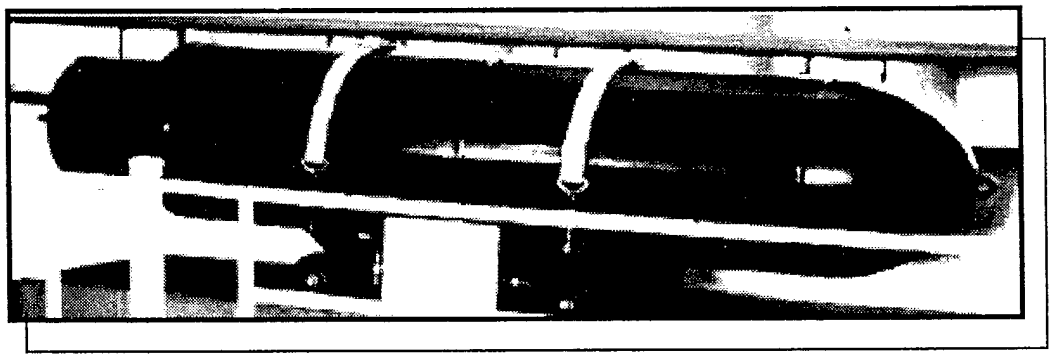
CONTACT MINES

MINE WARFARE

SMART MINES



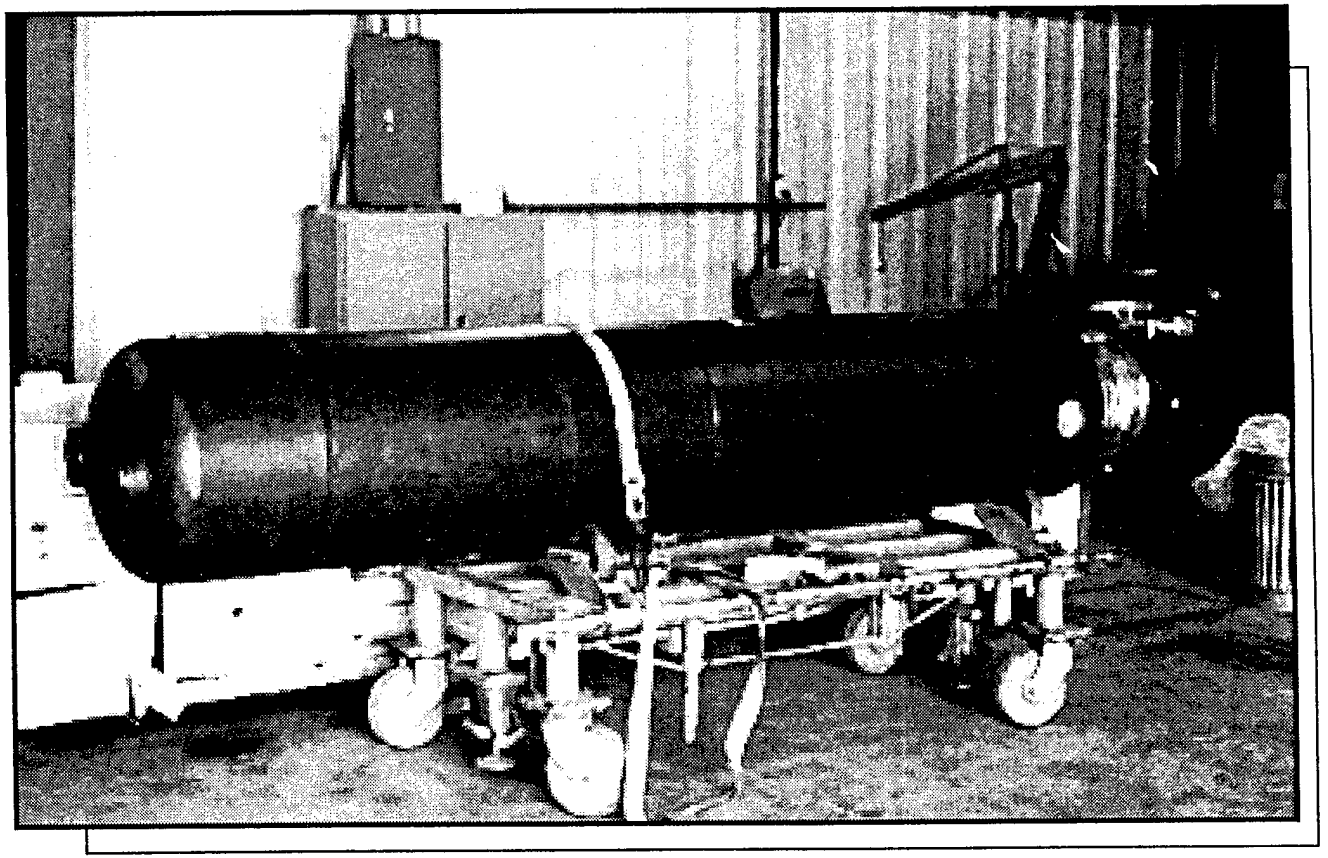
EM 53 - ROCKET PROPELLED



EM 11 - BOTTOM MINE

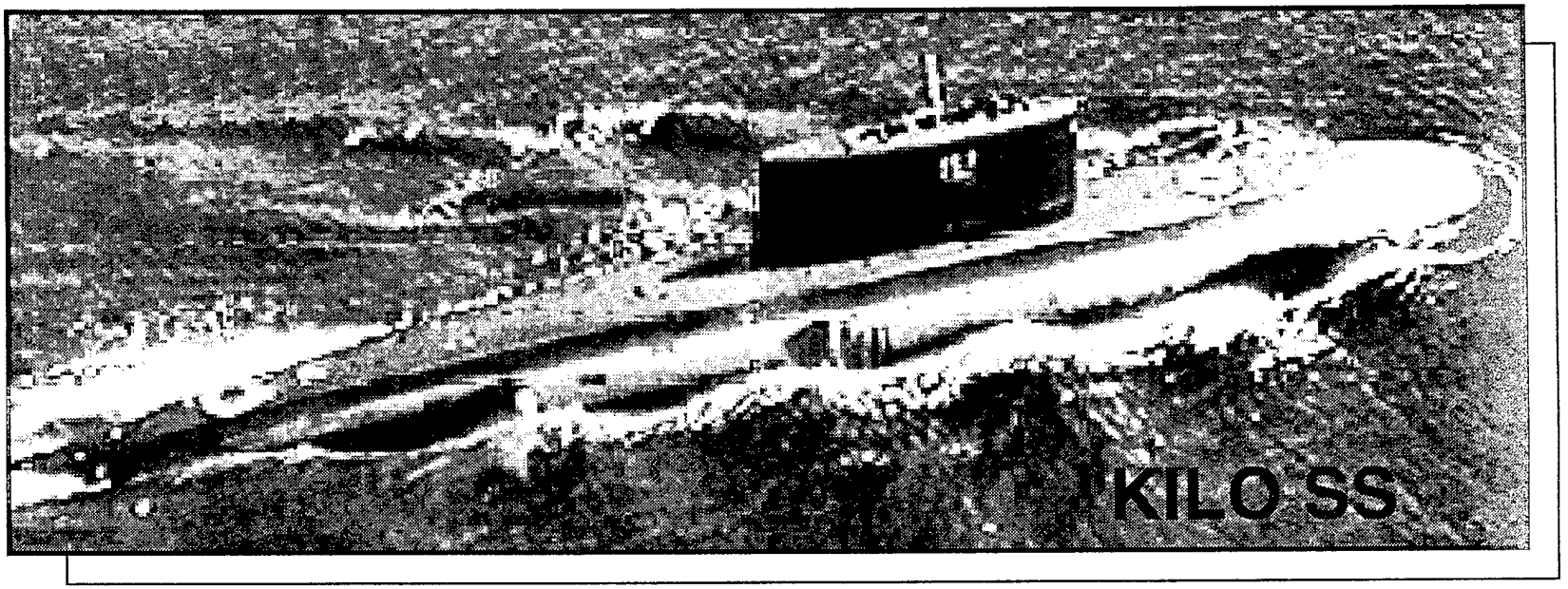
MINE WARFARE

SMART MINE



Advanced Bottom Mine
AMM - 230

MINE WARFARE

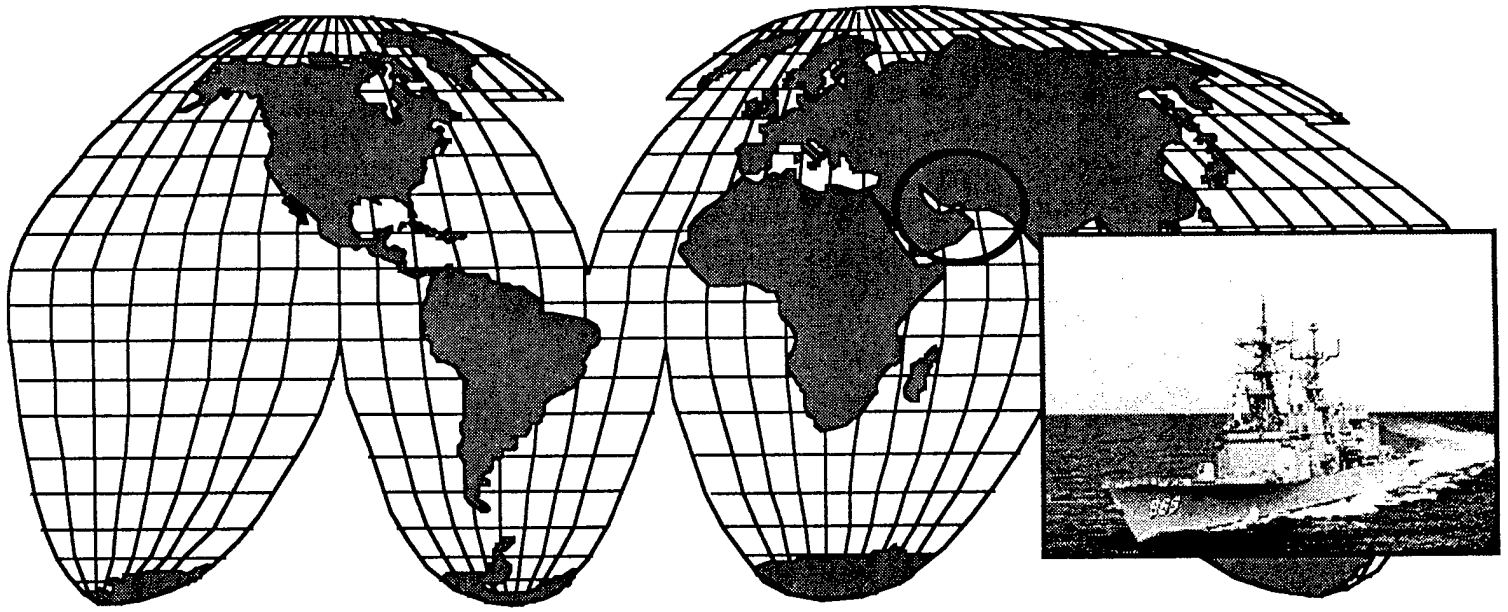


MANNED MINE

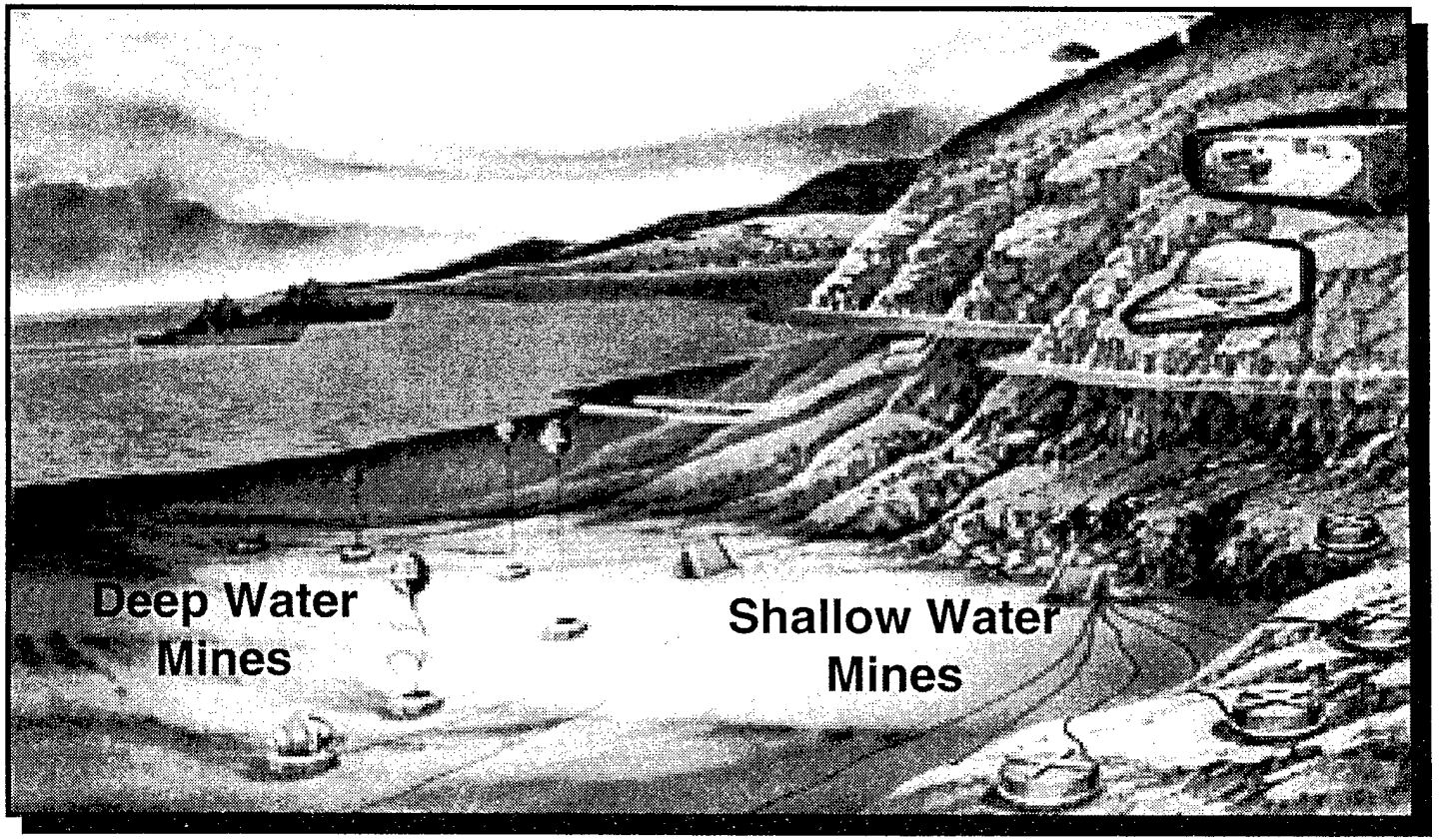
BACK-UP SLIDES

MINE WARFARE
LITTORAL ENVIRONMENT

- **Single most attractive weapon to inhibit U.S. Naval force projection from the sea**



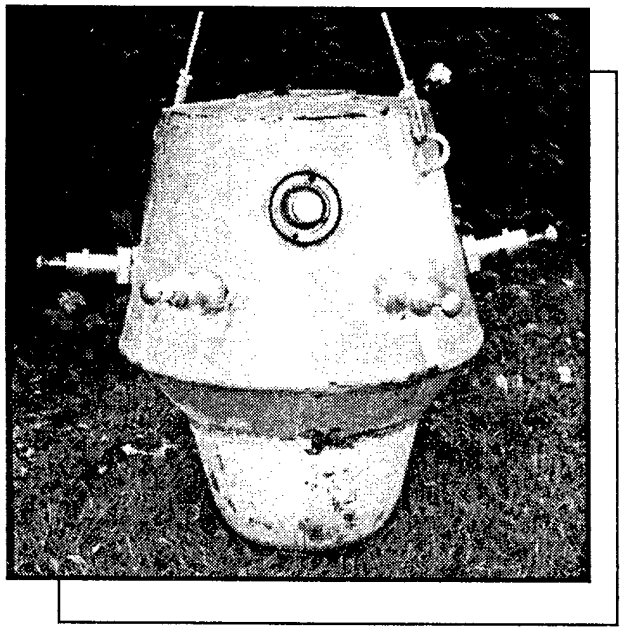
INTEGRATED MINE FIELD

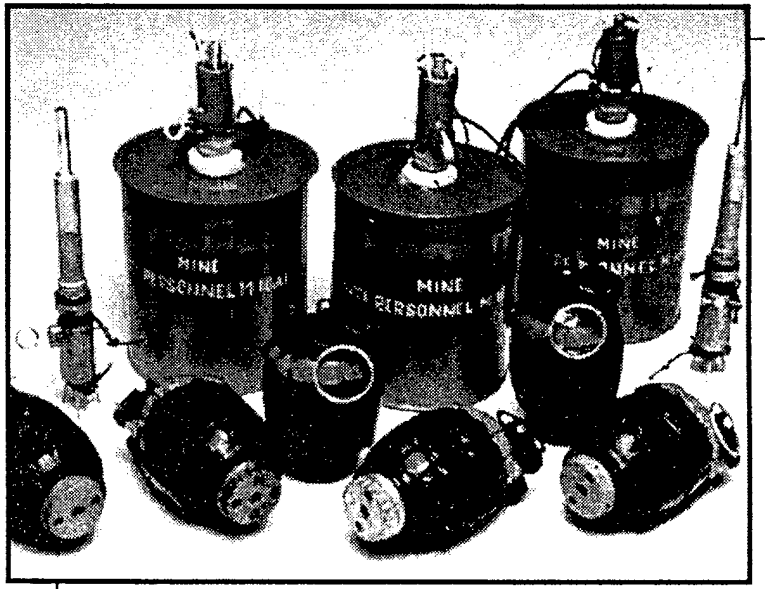


- **Landing areas mined**
- **Mine field protected by shore batteries**

Mines are available to forces that would otherwise be inferior

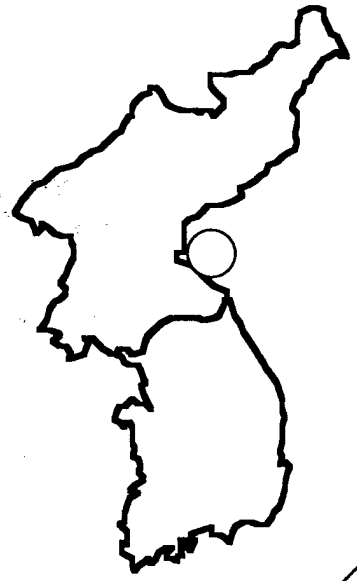
- **Mines are a "force equalizer.,"**





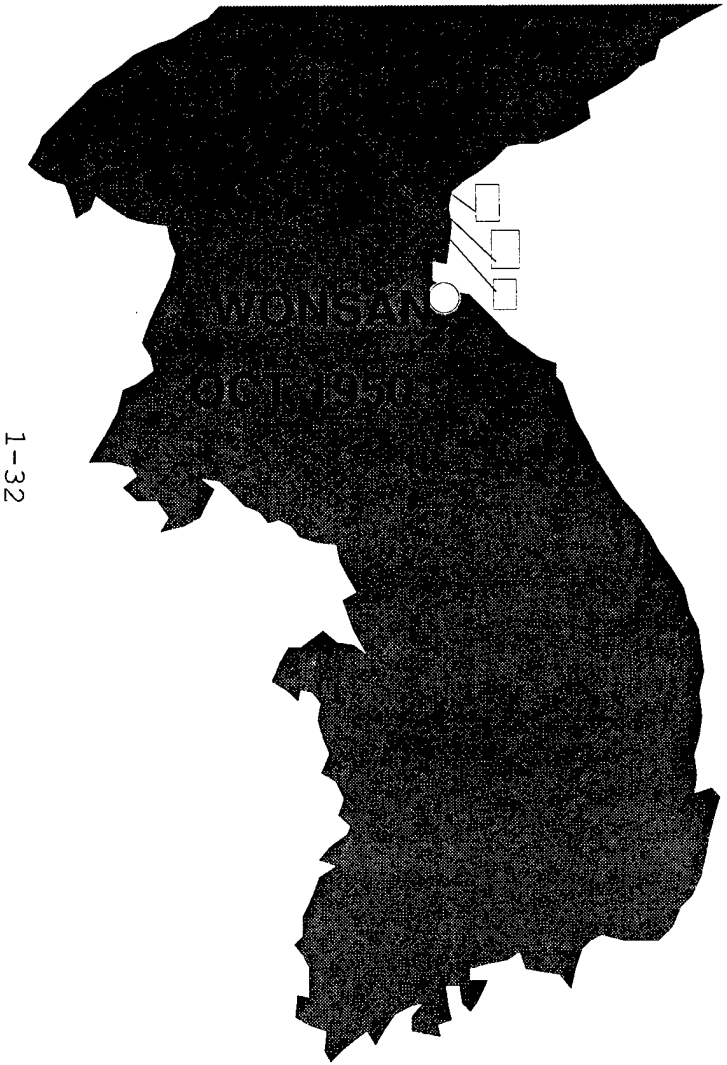
NORTH KOREA
10 October 1950

- U.S. mine sweepers began operations Wonsan Harbor
- Operation was to clear mines in support of amphibious landing forces
- Operation degenerated - four vessels destroyed
- Landing delayed 5 days
- Landing became irrelevant
- (Proceedings Sept 96)



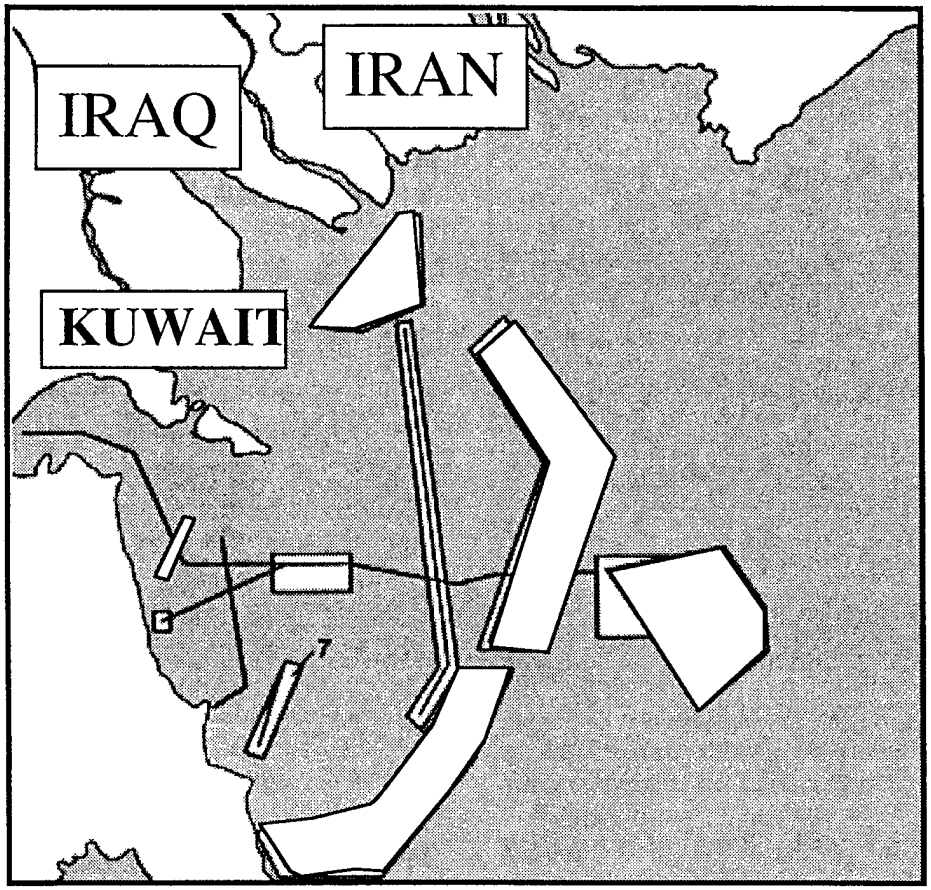
Mine Warfare

(Korean War)



- **250 Ships**
- **50,000 man landing force**
- **Mines laid by small boats delayed landing nearly a week**
- **3000 mines over 400 square miles**

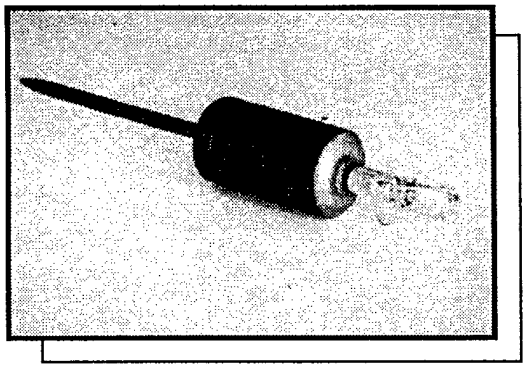
Mine Warfare
(Iraq)

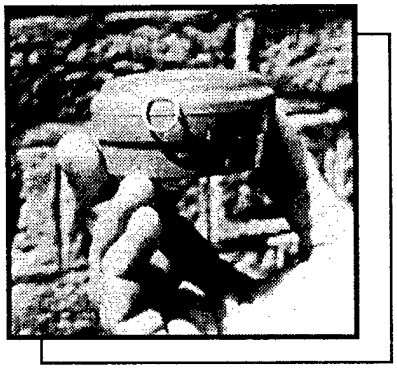


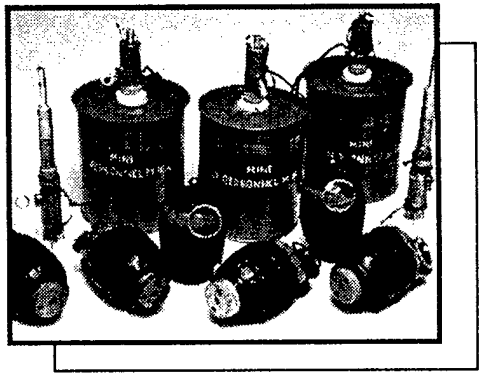
- **Over 1,200 mines located and destroyed**
- **Mines placed by**
  - **Minesweeper**
  - **Salvage/rescue ships**
  - **Utility landing craft**

Humanitarian Demining

- **69 Countries Affected by Landmines**
- **125-175 Million Landmines Buried World wide**
- **U.S. Military and NGOs Supporting Demining Efforts**
  - **Bosnia**
  - **Cambodia**







Technology, the Budget and Politics

ADM Stan Arthur, USN (Ret.) *

You have heard from a variety of speakers: GEN Sheehan, RADM Pearson, RADM Denny Conley and others who have recounted the history and menace of mine warfare from colonial days through our latest full-blown conflict in the Persian Gulf.

One of the major lessons of the Iran-Iraq War has to do with the continuing menace of even relatively low-technology seamines. When we were providing tanker escort through the Gulf, the Supertanker *Bridgeton* hit a 1908-designed mine laid by the Iraqis the night before, tearing a 30 foot by 40 foot hole in her 2-inch steel hull. (Bill Mathis, the escort commander who is in the audience, proved that surface warriors are not very smart -- he went through the minefield twice!) The *Roberts*, the *Tripoli* and the *Princeton* are all examples that have been cited during the conference of how deadly and inexpensive mines are, and how a militarily inferior country can use them to their strategic advantage to effect a political or military outcome. The cost to taxpayers to repair the damage to these ships totalled about $21.6 million. The cost of the two mines has been estimated at about $15,000 -- a great return on investment.

Generals Sheehan and Howell have described the strategic and economic SLOCs and outlined their concerns regarding our capacity as the only superpower in town to effect the ability to maintain freedom of the seas and rights of passage in the face of a real or perceived mine threats.

I would like to share some perceptions and conclusions I came to regarding mine warfare and its effect on the battlespace and overall campaign planning during my tenure as C7F and as the Naval Component Commander during Desert Shield/Desert Storm.

As early as 1990, it became apparent to us that the Iraqis had begun a massive defensive mining operation in the northern Persian Gulf. We were seeing that the minelayers were going to sea every night and coming back every day. And we knew they were popping in somewhere between 40 and 80 mines each night. Before we took action, Iraq had laid 2,500 more mines. This proves once again what RADM John Pearson has emphasized -- that the best countermine operation is to destroy the inventory at the source.

The first Symposium focused on underwater autonomous vehicles. It provided tangible results from industry that we are already starting to see. The RMS and LMRS are just two of the programs that got a boost from that first Symposium.

This Symposium has tackled the problem of how technology fits into the mine warfare problem and how it can bring innovative and rapid solutions to a very, very difficult warfare area.

* ADM Arthur was introduced by ADM Thomas B. Hayward, USN (Ret.), former Chief of Naval Operations and Honorary Chair of the Mine Warfare Association. ADM Hayward had been introduced by RADM Charles ("Chuck") Horne III, USN (Ret.).

We have made a lot of progress since the Iran/Iraq War and Desert Storm. The Navy's recent focus on mine warfare suggests it has gotten the message and is now placing a significant level of effort into improving mine countermeasures (MCM) capabilities.

We now have 14 oceangoing mine countermeasures ships. These 1300-ton wooden vessels are equipped with the most sophisticated combat weapons system in the world. The Avenger class MCM is a fully equipped MCM ship capable of crossing the oceans on its own power and of operating for up to 30 days without replenishment. These vessels were designed to counter the modern mine threat. With capabilities to conduct mine hunting and minesweeping, both mechanical and influence, these modern ships provide us with a far better capability than the MSO ships we had in the Persian Gulf.

The introduction of 12 coastal minehunters, the Osprey class MHCs, into the fleet is well underway. The MHC is an 800-plus-ton vessel constructed of glass-reinforced plastic (GRP). The program is an example of what you can do with existing technology, in this case GRP technology transferred from Italy. Please note that, in this case, the transfer of technology was positive, as opposed to another transfer of technology from Italy to a not-so-friendly country, Iraq.

You heard RADM Conley tell you that he intends to deploy three MCMs and one of these coastal minehunters to Denmark to participate in Exercise Blue Harrier -- the largest mine warfare exercise in the world.

During Desert Storm, we diverted an LPH (the *U.S.S. Tripoli*) from its primary amphibious mission to serve as a support ship for the MH-53Es. This took away a valuable Marine Corps lift. To provide command and control functions and a platform for airborne mine countermeasures helicopters and to support mine warfare operations, the Navy has converted the *U.S.S. Inchon* into a Mine Warfare Command ship. *Inchon* will carry an MCM Group Commander and his staff and will provide support to surface, airborne and underwater MCM operations without degrading Marine Corps amphibious lift capabilities.

To respond to the integration of mine warfare forces into fleet exercises and deployments, the Navy has an aggressive fleet exercise program underway. Mine warfare is playing a prominent role in Joint/Allied exercises. Our MCM crews are showing up and performing well. Our crews have participated in Blue Harrier, Kernel Blitz, JWID '95, Foal Eagle, and other exercises.

As RADM John Pearson pointed out, the CINCs want to integrate mine warfare and mine warfare forces into every work-up, with the MPSRONS and Marine ARG/MEU's. In fact, the demand for more mine warfare assets to participate in exercises and work-ups is far greater than RADM Conley can yet provide.

The focus is now shifting to developing and providing an organic MCM capability in our deployable forces. This capability is needed to find minefields at forward deployed areas with organic systems. We can no longer wait days, weeks and even months to execute plans while MCM forces transit to operating areas. A Remote Mine Hunting (RMS) System is now under contract to provide the fleet with a mine reconnaissance capability. A prototype developed during FY '94 and

successfully demonstrated during Kernel Blitz '95 is now being deployed on board *U.S.S. Cushing* with the *U.S.S. Kitty Hawk* battle group.

In order to improve response time to a fast-breaking crisis, four minehunters are now pre-positioned at overseas locations. Two are deployed in the Middle East and two more in the Far East.

But let's move on to more advanced technological systems. A laser-based system will soon be fielded to provide the Navy with a capability to quickly survey an area suspected of mines. The two systems, ATD-111 and Magic Lantern, will have a fly-off competition in April 1997 to determine the Navy buy. Both systems show promise of detecting underwater and partly buried mines, particularly in the surf zone. This will provide us with a long needed rapid reconnaissance tool.

A program is underway to replace legacy systems and electronics with Navy standard computers and work stations. The Integrated Combat Weapons Systems (ICWS) will reduce infrastructure costs while improving capabilities. The Program Executive Office for Mine Warfare (PEO-MIW), RADM Williams, has placed the highest priority on reducing life cycle costs while simultaneously seeking ways to improve mine warfare mission effectiveness. For instance, borrowing techniques from commercial off-the-shelf equipment allows us to reduce the number of printed circuit boards to 44 from 744. And this is just the beginning. This approach will provide the much needed improvements in reliability and maintainability. The estimates on the life cycle cost avoidance are approximately $400 million for just the first two phases of the program. This program is targeted for both MCMs and MHCs.

Over the years, computers and workstations have become more powerful at significantly lower costs. The Integrated Combat Weapons Systems will take advantage of the latest available computer and display technology to meet the emerging requirements of mine warfare ships.

Advances and improvements in other areas, such as shallow water MCM, minesweeping and lane clearing, are underway both in industry and in Government labs. These systems will provide a much needed capability to find minefields at forward deployed areas without the immediate need for MCM ships. MCM ships will be needed to follow up with hunting and clearing operations.

We are far away from solving the majority of mine warfare problems that exist from deep water, through the surf zone and up the beach, and through the entire battleground. There probably will never be that "Silver Bullet" you've heard about to shoot the threat of mine warfare in the heart and kill it. But I believe the powerful combination of our Defense labs and industry R&D can provide us the technology to overcome the "show stopper" effect that mines can produce.

Underwater autonomous vehicles, long-range autonomous vehicles, robotics, improved C4I for these systems, world class data bases with environmental and physical characteristics of littorals, improved tactical planning tools for the CATF and BG commanders, improved intelligence systems, clearing and breaching systems using brute force and advanced pulse power or lasers, buried mine detection systems, and improved integration of surface, subsurface and airborne assets are all being actively pursued and are within the technological and production capabilities of the United States and its allies.

The harder part of coating that bullet with silver is maintaining the interest of Congress and the budget masters that Mine Warfare is as important in the food chain as the SSN, CVX, new attack fighters, and other more glamorous and 'sexy' programs. It is the task of the attendees at this Symposium, whether active duty or industry, to get this message out. Because, if the greatest fighting force the world has every known can't put troops ashore during a conflict, it becomes a blockade force with limited ability to carry out national policy or exert force in the name of freedom.

We have the capability. Go out and convince others that we need the proper funding to bring the end products to fruition.

I know this has been a Navy water-oriented brief. I don't envy the ground pounders' problem, with probably ten times the amount of mines to encounter with the addition of anti-personnel, trip wires and booby trap features, that don't exist in our sea mines. But remember that only one sea mine can kill 600 sailors in an instant -- not a happy incident for a grandmother in Peoria or a Commander-in-Chief looking for re-election. So, I am prejudiced, but I think I understand both sides of the equation.

In closing, let me leave you with a simple way to remember how I view the mine problem. It's by the acronym PIMSA. P is for Prevention -- an ounce of prevention is worth a pound of cure, or, in this case, weeks of searching and sweeping. I is for Intelligence -- Essential Elements of Information (EEI). We need to know numbers, types, intentions, storage locations, methods of deployment, etc. M is for Mapping. We must be able to precisely locate not only the fields but also the disposition of various types of mines within those fields. S is for Swiftly Sweep/Neutralize only what is essential to accomplish the task. And A is for: And when all else fails, remember the words of a wise and masterful leader in our earlier encounters with mines -- "Damn the torpedoes (mines)! Full speed ahead!"

Again, I want to thank the Mine Warfare Association and the Naval Postgraduate School for the invitation to speak tonight, and Admiral Thomas Hayward for his kind words of introduction. Full speed ahead -- and good night.

Technology and the Mine Problem: An Evolutionary Revolution

Prof. Albert M. Bottoms
Ellis A. Johnson Chair of Mine Warfare
Naval Postgraduate School

I. INTRODUCTION

With the end of the Cold War and the lessening of the threat of instantaneous annihilation from nuclear attack, new sets of military and terrorist problems re-emerge. Prominent among these is the problem of mines, a problem - as was demonstrated in Kuwait - that required no time to come to the forefront. The fact is that mines have always been a weapon of choice for technologically and materially inferior groups. The 125-175 million land mines currently in place around the world attest to their popularity with rogue groups and insurgent forces as well as with conventional military establishments.

There are three conditions that must be met if the United States can manage the threats posed by mines and can take the lead in providing the technological applications to the solution of the problem of Humanitarian Demining:

*Availability of technological approaches and options,
*Command-level awareness of both the mine threat and the technology-based potentials for mitigating the threats, and
*Adequate and stable human and fiscal resources.

This paper addresses each of these conditions but places emphasis on the first, the promise and availability of technologies to bring about core changes in the arts of Mine Warfare.

Command-Level Awareness of the Mine Threat and of the Promise of Emergent Technologies.

This condition is met or nearly so in the Navy-Marine Corps - perhaps a little less so in the Army. Kuwait served as a powerful "wake-up" call to the Navy-Marine Corps team. Kuwait reminded us of what is meant by Command of the Sea. The Marine Corps, in addition, added Chapters to the basic Sea Strategy "From the Sea" to come up with the concepts of Operational Maneuver from the Sea. There is insistence on seamlessness as we pass from the water domains to those of land - and a recognition that seamlessness must extend to the link-up with Army land maneuver elements.

It is now common to see high-level Marine representation at meetings and symposia about Mine Warfare - representation that

simply did not exist even 5 years ago. Certainly some of this improvement results from the creation of the Directorate of Expeditionary Warfare in the Office of the Chief of Naval Operations. This directorate has been led by a senior Marine Major General since its inception.

Appreciation of the potentials of technology is growing. The Symposium on Autonomous Vehicles in Mine Countermeasures at the Naval Postgraduate School in April, 1995, provided focus for an array of technologies. This symposium was unusually well attended by senior Navy and Marine Corps officers. Their very presence lent impetus to the growing appreciation of the roles for technology.

Adequate and Stable Human and Fiscal Resources.

At this writing, we cannot say that this condition is fulfilled. There are severe pressures on R&D and procurement budgets. In such times there is an altogether too great a willingness to sacrifice R&D and force modernization programs. Needed are the tools and understanding for correctly apportioning available resource.

II. Modern Mines in Military, Paramilitary, and Terrorist Applications

A. A Brief Look at Mines and Obstacles. Mines are essentially strategic weapons, or tactical weapons applied to bring about a strategic outcome. The first "robotic" weapon, mines have been termed "weapons that wait". In the hands of terrorists or rogue groups, mines have also been termed "weapons of mass destruction in slow motion". In military operations on land and at sea, mines are used to delay operations or logistic support or to deny areas or to "shape" the battlefield. Mines and obstacles used together magnify the penetration difficulties, vitiate certain courses of action, and present a qualitatively different problem for the would be transitor. Mines and obstacles are readily available to groups that are otherwise numerically and technologically inferior. In this sense, mines and obstacles are "force equalizers".

Anti-personnel land mines are emerging as the scourge of the Twentieth Century. Estimates are that in areas of the world that are or have been contested land mines in place number 125-175 million and cause 2000 killings and maimings per month. The lingering effects - long after cessation of immediate hostilities - is what terrorists exploit.

Some Historical Examples. The anti-shipping campaign by the Germans against Britain with magnetic mines was nearly decisive as a weapon of blockade. The strategic mining campaign against Japan,

OPERATION STARVATION, coupled with the anti-shipping campaign conducted by American submarines brought the import of strategic materials virtually to a halt before Hiroshima.

Since World War II mines have figured in every armed dispute; Vietnam, both sides and in both Indo-China Wars, Bosnia, Nicaragua, Korea - most effectively by the North Koreans, and at Kuwait. The American mining of Haiphong is credited with forcing the release of American Prisoners of War. The mining of the escape routes for the Iraqi Revolutionary Guard in their retreat from Kuwait immobilized those units and set up the devastating "killing zones".

In view of the "leverage" that offensive mining confers, it is surprising that this strategic tool is not better understood, and considered, in American security planning. Similarly, the U.S. Navy cannot be allowed to forget the impacts of Wonsan and Kuwait. Simply put, "the U.S. Navy lost command of the seas to countries that didn't even have Navies" - an observation by Dr. Tamara Melia Smith at the First Menneken Lecture on Mine Warfare at the Naval Postgraduate School, September, 1994.

B. Numbers and Types (A Synopsis of the Variety of Mines, Obstacles, Booby-traps, etc.). Generalizations about mines can be misleading. What follows is generally, but not absolutely true. The first point to take is that the collections of families of mines represent a complex and overlapping set of weapons. The second point, applicable to sea and land mines, is the world-wide proliferation of the most sophisticated mines and mine components. The third point, particularly true of land mines, is that they exist in stupefying numbers - over 125 million land mines already in place around the world.

The families of mines intended for use against ships are generically called naval mines. These can be further classified by where they are used - floating, moored, bottom, or buried. A further sub-classification results from consideration of the firing mechanisms - controlled[1], contact, magnetic, acoustic, pressure, and combinations that simultaneously complicate sweeping processes and "tailor" the mines for intended classes of targets. Also complicating sweeping are features such as delayed arming and ship-counts. An unarmed mine is simply an inert blob. Once activated

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[1]Controlled mines have been used to guard port entrances or other strategic waters. Controls can range from putting a mine (or field) in the status armed or safe to permitting an the firing of individual mines when targets approach. This technique was used by the Viet Cong and their predecessors, the Viet Minh in the river ambushes.

(armed) the miner protects the minefield from sweeping by using a distribution of ship counts that can range as high as 10. A ship count is what it says; an actuation by a ship or sweeper. When the count is one, the mine detonates upon the next actuation.

The use of ship counts defeats "escort sweeping" - running a sweep or low-value target ahead of a high value target. Ship counts and arming delays are settings that can be made at the time the minefield is put into place.

Minehunting, primarily by acoustic means but increasingly using optical or magnetic techniques, provides an answer to the "ship count" minefield. The mine designer's counters to minehunting are the use of non-magnetic materials and irregular or "stealth" shapes. The Swedish ROCKAN Mine has no parallel faces and a minimum of flat ones. It looks like a rock. The Italian "MANTA" mine is a truncated plastic cone with about 500 kilograms of explosive. Such a mine seriously damaged a U.S. warship during the Gulf War.

Land Mines. Much of what has been said about sea mines applies also to land mines. The main differences are the orders of magnitude differences in numbers of land mines and their relative ease of emplacement. The sources of doctrine for the use of mines are Anglo-American, German, and Russian (former Soviet Union).

The U. S. Army catalogues over 750 distinct mine types by mark and mod, country of origin, and manufacturer. As with naval mines, most of these land mines have several firing mechanisms - contact, trip - wire, acoustic, magnetic, pressure. Their application can be as anti-personnel mines or as anti-tank, anti-truck, etc. An interesting development is that of an "off road" mine that combines a mine actuation mechanism with a warhead equipped homing missile.

Where the typical naval mine can approximate the size of a desk, most of the land mines range in size from that of an orange to that of a small casserole. These mines are cheap - two to five dollars a piece for most of them. Anti-tank mines of the tilt-rod variety are somewhat larger and more expensive, but most of the anti-personnel mines weigh just a few pounds.

Obstacles. Incredible as it may seem, mines and obstacles have been considered as separate problems until very recently. Now obstacles are considered to be part of the mine countermeasures problem. Obstacles are a very unwelcome addition to the problem as they effectively defeat use of explosive nets for clearance of anti-personnel mines while being resistant to all but the largest explosive charges.

The catalogue of obstacles - all of which are available to any

determined groups - include barbed and concertina wire (often sprinkled with anti-personnel mines and grenades), hedgehogs and welded iron tetrahedrons, primitive Jersey Barriers (weighing up to 4000 pounds), and cement blocks that may weigh up to 10,000 pounds. The practice is to intersperse such barriers with anti-personnel mines so that engineer sappers cannot emplace destructive charges or use wire-cutting devices. The organization of the beach defenses at Kuwait by the Iraqi show how quickly extensive and formidable defensive positions can be organized.

C. What Mines Do. Mines sink or damage ships, destroy or incapacitate vehicles, and kill or maim individuals. Based upon demonstration of these very real effects from the use of mines there are the psychological threats of a lurking, unseen weapon. It is a grave mistake to underestimate the psychological impact of mines.

The above are the direct effects of mines. The indirect effects are the disruption of timetables through introduction of delays occasioned by time-consuming mine countermeasures operations. These delays, in turn, permit the defenders to concentrate forces and firepower on the attacking force.

When mines are used at sea - port entrances, choke-points, or even in strategic areas such as the North Sea; the very presence of mines causes "virtual attrition" due to the speed or course modifications forced upon the transiting forces or elements. Virtual attrition is defined as the number of additional ships needed to ensure safe and timely arrival of overseas transport at the same cargo-delivery rate as in the unimpeded case. That is, if x shiploads per week meet requirements in the absence of mines, and y shiploads per week are needed to make up for the transit delays, then the virtual attrition is y-x. In practice, the virtual attrition is of the order of x.

III. The Physical/Operational Environments of Mine Warfare

Introduction: Mine countermeasures activities and planning for equipment development and acquisition have been hampered by lack of precision in descriptive language and failure to recognize in explicit terms the totality of the assets, present and potential, that can be brought to bear. The technical phrase, sub-optimization, and the graphical phrase, stovepiping, describe the motivation for defining the manifold that makes up the kit or armamentarium of mine countermeasures. A synonym for kit or armamentarium is tool box.

What must be done, where the activities take place, and the

military or civilian context define mission, environmental, and contextual niches or classifications for the principal uses of MCM hardware. These are the bins of the MCM "Tool Box". Those niches subdivide the time domains of present, near term, mid-term, and far term. Introduction of the time domains immediately suggests that the system-of-systems approach to MCM is an evolutionary one - albeit with some revolutionary elements conferred by emerging technologies.

People. At the outset let it be noted that each system or subsystem consists of hardware and people. An objective of many of the developments is to reduce the hazard to individuals who are engaged in mine countermeasures activities while increasing the effectiveness in both military and economic terms of operations. Individuals who are directly concerned with mine countermeasures activities must be highly trained and experienced in the art of mine warfare. They must be resourceful "problem solvers" who possess intimate knowledge of the hazards they face as well as sufficient knowledge of the capabilities and limitations of their tools to make efficient selection of mine countermeasures approaches[2]. Such individuals are, by definition, well-suited to train indigenous or inexperienced personnel in operations specific to a locale or to pieces of equipment.

Education, training, and experience are the hallmarks of this breed of specialists. A 1992 Report by the Naval Studies Board of the National Academy of Sciences noted the importance of graduate-level education in the scientific underpinnings of the operations, sensors, environments, and weapons characteristics for those in leadership roles. Equal emphasis is given to maintenance of cadres of individuals with both classroom and hands-on training in mine countermeasures.

The Niches within the Time Domains.

a. Contexts.

1. Military combat. The requirement is to bring the risks to an "acceptable" level in a timely manner. The terms acceptable and timely are related and are military situation dependent. This contexts is often associated with amphibious assault or minefield breaching in the land-warfare context.

2. Military administrative. Clearance of relatively limited areas for logistics support or administrative use but in an overall

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[2] The operators and leaders of mine countermeasures operations can be likened to groups of MCM Red Adairs, after the legendary individual who puts out oilfield fires.

hostile environment. Assurance of minimal risk is the desired criterion.

3. Civilian administrative (Humanitarian Demining). This differs from Military administrative in that a high degree of **Assurance that an Area is MINE FREE** is required over potentially huge areas. Furthermore the measures of effectiveness include economic terms as well as suitability for employment by minimally trained indigenous personnel. And the measures are also in terms of human suffering, the killing and maiming of innocent civilians, often women and children. Anti-personnel mines are designed to maim and maim they do.

Humanitarian Demining is a subject unto itself. It is a qualitatively different problem than the usual military mine countermeasures operations. In addition to the staggering magnitude of the tasks in the under-developed parts of the world, it will be necessary for economic reasons to rely primarily on indigenous capabilities - trained and assisted by United Nations and American armed forces. While Humanitarian Demining operations can take place at times that suit the deminers and at paces that are slower than that of combat operations, the operational requirement for "assurance that an area is mine free" is a tough requirement.

b. Missions or Tasks. (Consider separately as covert or overt capabilities).

1. Intelligence - Information about mine sources, stockpiles locations, inventories, employment doctrine, logistics networks and nodes, enemy C4I, mine hardware characteristics, and indicators. There is concern about both production marks and mods of mines and "homemade" mines and mine-like devices such as booby traps and obstacles.

2. Reconnaissance - Determination of the extent of mined areas, the nature of the mine threats within those areas, and activities that support the minefield such as covering fires or replenishment capabilities. An important aspect of reconnaissance is the real-time or current state of environmental variables that affect the performance of MCM equipment.

3. Detection and Classification of objects as mines.
4. Identification of Mine-Type or genre.
5. Marking of the Object (for return or for avoidance)
6. Removal or Retrieval of the object.
7. Neutralization also called Rendering Mine Safe
8. Destruction of the mine or mine-like object.

In the military context of a(1) above, these activities constitute breaching or assault mine countermeasures. Note that these tasks represent niche sub-divisions.

c. Environments. The Symposium on Autonomous Vehicles in Mine

Countermeasures lent additional emphasis to the 1992 Naval Studies Board MCM Review in which, for the naval applications alone, the major "niche" environments were subdivided according to water depth in the ocean and by physical/biological subdivisions in estuarine and riverine domains. Similar physical and vegetation divisions exist in the land environments. The following niche identifications may be subject to modification, but are offered as a starting point:

Naval Domains:

1. Deep Ocean (<100 Fathoms)
2. Shallow Water (40 - 600 feet)
3. Very Shallow Water (10 - 40 feet)
4. Surf Zone
5. Estuarine
6. Riverine Including lakes)

Because of the physics that govern sensor performance, the above must also be categorized with respect to presence of man-made or natural mine-like objects, salinity, turbidity, electrical conductivity, and possibly other characteristics such as the presence/absence of biological and botanical organisms and plant growth.

Land Domains[3] (Subdivided by Presence/Absence of Vegetative Cover (trees, bushes, of grasses))

7. Rocky
8. Sedimentary
9. Sand (Dry Desert)
10. Sand (Moist/Beach)
11. ice and snow cover

As with the naval domains, the land domains must be grouped by similarities in the physical properties that determine sensor performance.

Affecting sensor performance - particularly airborne or space-borne sensors - are such aspects of the physical environments as the nature of electro-magnetic noise, daytime and nighttime reflectivity at wave lengths of interest, weather patterns, and so on. Clearly, precision must be introduced into the categorization of the anticipated performance potentials of MCM equipment under development.

The above defines the bins for the tools of mine countermeasures. Next, a motivation for having a taxonomy is provided.

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[3]These classifications are subject to refinement into joint domains of climate class (for vegetation) and for soil class (for soil/geological characterization according to physical characteristics).7

Potential Utility of an MCM Taxonomy in System Development and in MCM Operations

Development Advantages. With limited resources, we want to make sure that systems under development have both relevance to the mission needs and applicability in domains of greatest potential military or humanitarian interest to the United States. We want to avoid making good enough better, and avoid addressing situational outliers. We do want to address major known deficiencies - especially those that directly impact operational capabilities in regional situations of high interest. Implied here is the necessity to develop a qualitative or semi-quantitative scheme for assessing the adequacy of the collection of "tools" that occupy each of the bins. Note that defining the mission tasks helps in this regard.

Operational Assessment of Capabilities. A philosophical note is in order at the start of this part of the discussion. The MCM development community has become so intrigued with the technological contest between the mine designer and the designer of countermeasures - admittedly a necessary focus where mine clearance and area assurance are required - that the larger operational aspects of the role of mines is lost sight of.

In a great many military applications - sea control, area denial, "terrain shaping", etc. - the minefield is the weapon; the individual mines, the weapons system components. One doesn't try to neutralize an infantry rifle division by attacking the rifles. Why do we do the analogous thing with the minefield?

Go where the mines aren't! Or go in such a manner that they can't reach you. In practice this means going around or over the minefield or, in some situations, exploiting a breach before the miner can replenish. In practice, accomplishment of either of these approaches involves intelligence and reconnaissance (covert and overt) and the means to move the troops and materiel at rates more rapid than the rates at which the miner can respond with mines or other covering weapons systems.

In a Kuwait-type scenario, consider some of the systems implications of the above approaches to countering the minefield. Operational maneuver coupled with tactical deception and operational security are techniques to prevent the enemy from concentrating forces and covering fires in the intended assault areas. Intelligence and reconnaissance (covert) establish boundries, if possible, for the minefields in the water and the minefields and obstructions on land at least to the planned craft landing zones or beyond. The mission of reconnaissance also includes establishing the enemy "order of battle" and the locations of air, missile, or artillery covering the minefields or, as

importantly, enabling the enemy to establish "killing zones" is supposedly weak or unmined areas (traps). In this scenario, early defense suppression by strike air, missiles, and naval gunfire are very important precursors to any attempt to circumvent of breach the minefield. (The vital role in mine countermeasures operations that is played by elements capable of offensive power projection is rarely explicitly called out. It should be as it was during the Normandy Invasion). The composition of the striking forces and the weapons load-out for these forces must also reflect the defense suppression and objective areas preparation requirements.

There are roles and tasks for specifically configured and dedicated MCM assets in this reconnaissance phase. Here lie some of the opportunities for MCM technologies to augment human resources and minimize the risks to those resources. This aspect will be covered more fully in a later section of this paper.

Intelligence and reconnaissance can effectuate avoidance of minefields. But what are some of the ways that breaching or logistics follow-up assets can "go over" or reduce the risks of mine damage? Here again are sets of "non-traditional" mine countermeasures. One is saturation bombing with very large bombs - not a panacea, but worth some focussed, developmental effort.

Another is use of aerial tramways as adjuncts to vertical assault. Yet another is the construction of causeways on beds of plastic foam, or earth, or pontoons. This leads to other applications of heavy, earthmoving equipment also in the hands of Combat Engineers or Seabees. These alternative approaches will not be possible if they are not explicitly included in the MCM "Tool Box".

Then there is a set of passive mine countermeasures that are organic to the craft and vehicles that must traverse mined areas - signature reduction, explosion resistance, and personnel protection. An advantage of many of the passive mine countermeasures is that they are largely domain independent (except for the engineer causeways).

Of course, one can expect that the well-designed minefield will have some counter-countermeasures features. Today, it is common to find anti-personnel mines "protecting" anti-tank mines and obstacles. This practice discourages pathfinding and the use of explosive nets that must be deployed by personnel. It is prudent to identify the capabilities and the potentials for counters to each of the mine countermeasures component systems. Here again there are two kinds of considerations; the first, does an enemy possess the technology and infrastructure to field counters. The second, can the enemy field counters within the time and logistics constraints of specific operations.

IV. Emerging Technologies Supporting the Mine Warfare Paradigm Shifts and "Evolutionary Revolution"

Emergent technologies are enabling the paradigm shifts in Mine Warfare. These technologies contribute to the intensification of the threats from mines through the explosive proliferation and availability of sophisticated mine mechanisms. Technology also offers the potential for biological, chemical, and radiological warheads. Already available to rogue groups are land and sea versions of mines capable of effective damage at stand-off ranges - the so-called "off road" mines that can be thought of as land versions of our CAPTOR mine.

In mine countermeasures/countermine, the technology explosions in navigation, sensors, control, C4I, mine neutralization packages, and "on board" or "organic" counters amalgamate to the "system of systems" that comprises Mine Warfare.

This portion of this Paper highlights some of the cutting-edge technology developments that singly and together can dramatically change the ways that we approach the Mine Problem on the sea and on land; in military operations and in carrying out the collection of activities called Humanitarian Demining. Perhaps as important as the scope and diversity of the emerging relevant technologies is the numbers and breadth of the academic, government, and industrial organizations that are engaged in both basic research and applications engineering. This is quite fitting. A national - even international - problem requires address on a national ,(and international) scale.

Put another way. There is a large, highly competent, decentralized R&D base capable of being focussed on the urgent problems of solving the Mine Problem. Needed is the "top-down", product-oriented management approach of the World War II Manhattan Project.

The approach for the rest of this Section of the Paper and for the following section is to progress from the general to the specific while attempting to minimize redundancy.

A. Identification of the Paradigm Shifts. Until the relative present, the Mine Force - mining and mine countermeasures - had a "stand apart" status, in but not of the first-line military organizations. Particularly in mine countermeasures there were dedicated platforms, minesweepers, MCM helicopters, and the like. The presence of ships and dedicated aircraft in a force created operational and logistical difficulties as the operational time lines of the MCM mission were inconsistent with the needs of the major Fleet and Amphibious units. A direct consequence of this

"separateness" is the widespread combination of ignorance of and distrust in the mine countermeasures forces.

Surveillance, Reconnaissance, and Covertness are key words in modern mine countermeasures. What was once just a wish has been enabled by emerging technologies - data fusion, information management, sensors from satellites or from aircraft (JSTARS), and the capability to emplace geophones or distributed acoustic monitors to "sweep" an area and note changes.

There remain some issues; education of battle staffs about the kinds of questions that must be asked and the kinds of data that are needed and accommodation to degrees of covertness, To hold out for absolute covertness in a reconnaissance or surveillance capability may rule out promising approaches. It appears that "covertness" is very much a function of what an adversary can do with compromised activity.

Platform independence, increasingly a hallmark of emergent systems, is a demonstrable paradigm shift in Mine Warfare. Platform independence refers to the ability to provide desired operational characteristics to non-dedicated platforms or vehicles. In mining, the affixing of mine rails to any class of surface ship confers a mining capability to that class. Parenthetically, it might be noted that this is exactly what the former Soviet Navy did.

The technologies of miniaturization, of power saving, of remote sensing and remote control, and the capability to amalgamate the distributed units into a virtual system all contribute toward the realization of mission-oriented "platforms of opportunity". Thus, one can imagine definition of "mine countermeasures kits" similar to the elements of the Advanced Base Functional Component system where a commander can order "MCM kits" for commandeered fishing craft, tugs, etc. Visionary? We did that to a degree at Suez in the Eighties.

Organic Mine Defenses. This is the term applied to "built-in" active and passive mine countermeasures capabilities. A familiar example is magnetic degaussing, one of the class of signature reduction measures. Another example is the family of mine avoidance sonars such as the Kingfisher Sonar that confers a mine avoidance capability to a surface ship. Technologies of sensors are already augmenting the eyes of the watchmen.

Increasing Degrees of "Supervised Autonomy". Concepts that use words like "robotic" or "artificial intelligence" conjure images of activities that are essentially uncontrolled or even subject purely to chance. These ideas are not consistent with what one needs in

military operations and activities where discipline and absence of unplanned events are the rule. However the technologies of communications, of systems control, and of vehicular design come together to promise generations of mine countermeasures systems that demonstrate a spectrum of degrees of supervised autonomy.

Today, we have some systems that have no autonomy - remotely piloted or teleoperated systems. These may be thought of as the "zeroeth" generation. Already demonstrated in reconnaissance drones and target drones are examples of the "first generation" of autonomous systems - those that follow pre-planned tracks or carry out programmed activities. Most of the vehicles used in space are representatives of this first generation of autonomous vehicles. In both generations there are provisions for "man-in-loop".

Under development are autonomous systems with increasing degrees of autonomy - or progressively less supervision. Some concepts involve "swarms" moving from deep to shallow water in pseudo-random paths. This is the second generation of autonomous systems and is already in prototype stages of development.

The more that is learned about biological systems such as dolphins or minehunting dogs, the more sophisticated the controls, the supervisory functions, can become. This line of development is the forerunner to the concept of the "Autonomous Mine Countermeasures Brigade" that is described in the last section of this paper.

Some of the enabling technologies behind these developments can be found in the emerging "Information Superhighway". These developments provide examples of technology transfer - in this case from the communications sector to military utility.

B. Surveillance and Reconnaissance. Modern mine countermeasures depends heavily on assets that are not organic or even controlled by the mine countermeasures force commander. The products of Remote-Sensing and Reporting from vehicles as varied as satellites, aerodynamic platforms such as U-2's and JSTARS, and Teleoperated Vehicles as Sensor Platforms over Land provide essential, real-time coverage of Land and Beach Environments and may contribute to the requisite mapping for Humanitarian Demining applications.

Water Environments (the Niches) can now be covered by Remotely-guided (man-in-loop) undersea vehicles. The future vision contains Autonomous Vehicles capable ultimately of combinations of Programmed search, Random Search, and Fully Autonomous Search.

C. Dealing with the Mines and Obstacles. In operational maneuver from the sea as well as in breaching operations in land warfare the objective is to is to pass through the mined areas as quickly and safely as possible. The term "in stride" is used to signify that an objective is to breach the minefields and/or land the landing force without slowing the troop and equipment-carrying vehicles. Clearly, it is most desirable to "go where the mines aren't" - thus the emphasis on surveillance and reconnaissance. If that is not possible then the mines and obstacles must be neutralized or removed.

What we do now. In the absence of heavy obstacles the approach is to use explosive nets or modified "Bangalore Torpedoes" to break a path through the minefields. That path is successively widened until means of ingress for landing craft exist. This approach can be called "Blow as you go". Heavy obstacles - dragons teeth, cement blocks, hedgehogs - defeat the nets. The interspersed anti-personnel mines prevent men from emplacing explosives or attaching slings by which the obstacles can be removed.

As of late 1995, the only obstacle clearing device is the CLAUSEN POWER BLADE. This proprietary device uses a novel "live" blade on a bull-dozer to brush mines and obstacles aside. Low tech but immensely effective! There is some possibility that application of the CLAUSEN BLADE technology can also be made to vehicles capable of operating in the surf zone.

The U.S. Army and the U.S. Marine Corps have or are developing families of rakes and plows that can be attached to a variety of armored vehicles and engineer equipment. One, the JAMC, is advertised to have some capability against light obstacles but has not been tested against the same stresses that the CLAUSEN POWER BLADE has (October, 1995, at Camp Pendleton, CA).

D. The Components and Elements of the Mine Countermeasures "System of Systems" - The Application Areas for Emergent Technology. This section might also be titled "The Building Blocks for the Autonomous Mine Countermeasures Brigade".

This section completes the tableaux that represents the mine countermeasures "tool box" - the mine countermeasures "system of systems. One dimension is the set of land and sea environments in which mine warfare may be encountered. The second dimension is the set of operational tasks that are required - some of which are scenario dependent. The intersections on the tableaux are filled by one or more candidate elements and components.

Without attempting to present a complete set of technological applications, the following provides a glimpse of the technological

scope in emergent modern Mine Warfare.

Vehicles - Displacement hulls, SWATH (Small Waterplane Area Twin Hull) craft as stable platforms, remotely controlled or autonomous platforms capable of operating on land, in the air, on and under the sea, and on the sea floor. Bottom-capable vehicles may be tracked, serpentine, Archimedes Screw - driven platforms.

For completeness, space vehicles, aerodynamic vehicles, and sensor-dispensing rockets and missiles also are in the mine countermeasures "tool box".

Sensors - On land the mainstay remains a non-magnetic probe, the modern equivalent to the bayonet. Also there are hand-held metal detectors. Technology promises area sensors such as Ground Penetrating Radar, microwave, infra-red and seismic. The electo-optical sensors have promise into the surf-zone and against floating and tethered mines. However, beyond the surf zone the principle sensors are acoustic with classification assist from magnetic and optical sensors. Development is underway on tactile sensors and on applications to mine countermeasures of electrical resistivity anomalies and electrical non-destructive testing techniques using eddy-current phenomena (Iowa State).

The Office of Naval Research has an active program in biologically-based sensors - chemical sensors (believed to be the basis for dog and pig capabilities against buried land mines) on land and sonar studies based upon observations of the capabilities of the dolphin, the only means for detecting and classifying buried mines.

Navigation and Control - The Global Positioning System (GPS) and derivative capabilities is a breakthrough that has already resulted in an order of magnitude improvement in current mine countermeasures capabilities. GPS and the more accurate Differential GPS provides the enabling technology upon which future autonomous and semi-autonomous (unmanned) mine countermeasures "tools" will be based. The importance is that a geographical spot can be revisited by other elements who will be close enough to the target of interest to reacquire the target with inherently shorter range sensors. GPS also provides the basis for internal navigation and control of individual vehicles as well as ensembles of vehicles.

The vision of the autonomous mine countermeasures brigade would lack substance were it not for GPS.

Communications . The technologies developed by radio amateurs for packet radio and by the telecommunications industry for

cellular telephones are finding their way into such emergent mine countermeasures surveillance and reconnaissance systems as the Autonomous Ocean Network. The C4I systems that permit the establishing of virtual environments are outgrowths on internet technologies.

Work Packages . The traditional mine countermeasures work packages are cable cutters, moored sweep gear, acoustic and magnetic sweep gear (towed cables and noisemakers capable of projecting bogus ship signatures to trick the mines into firing. There are analogues to these devices in the land mine clearance tool kit.

Two work packages that deserve mention in the land-mine/obstacle clearance case are the CLAUSEN POWER BLADE System(also heavy obstacle-capable) and the Wattenburg Plow, a helicopter drawn device capable of speeds of up to 20 kts over fields that are obstacle free. The first can be mounted on bulldozers, armored vehicles, and underwater work vehicles. The CLAUSEN system features a side-transporting moving vertical belt in place of the familiar bulldozer blade. The latter, the Wattenburg Plow, has retractable "knives" attached to a drawbar. Mines are uprooted and caught in a chain bed behind the drawbar.

Teleoperated or remotely-controlled vehicles can place charges on mines or obstacles that can be command-detonated. Such vehicles as well as the trained mammals can place cable-cutters or shaped charges on moored mines. On land, dogs and pigs have been used to mark suspicious contacts.

Work packages for autonomous vehicles - the potential members of the mine countermeasures autonomous brigade - remain largely undefined. Needed are means to attach chains or slings to obstacles or mines so that they may be removed from their locations. Also, it would be desirable to be able to use a small robot to affix a shaped charge on a mine or obstacle. In this case the positioning of the charge is important. Such activities will require Man-in-Loop for the foreseeable future.

It is significant to note that mine countermeasures is the beneficiary of a great amount of research and development into what ARPA calls "Taskable Machines". Every major research university has work in industrial robotics and in advanced control concepts that will lead to a broad spectrum of supervised autonomy approaches. It is this kind of research that leads to control of individual vehicles and ensembles of such vehicles. The processes begin with rule-based approaches and proceed to "learned rules" that might also be termed artificial intelligence. This area is of significance in enabling realization of the concepts of the mine

countermeasures autonomous brigade.

Tactical Decision Aids and C4I - New Tools for the Force Commander. The stereotype or mine countermeasures as repeated passes of minesweepers through an area is as outmoded as the "grease pencil" surface plot. Soon the commander will "see" the objective areas through the fusion of data and information from both technological and human sensing nodes. Mine countermeasures C4I has already demonstrated the ability to mirror events off the West Coast in the Gulf of Mexico. Such training and evaluation activities are by-products of the major efforts in distributed modeling and simulation that have been supported by the Navy and the Department of Defense.

V. The new set of mine countermeasures tools, the Autonomous MCM Brigade - A Vision for the Future

The recent symposium showed that the sets of technologies needed to field families of affordable autonomous vehicles capable of performing some or all of the tasks of mine countermeasures are within grasp. This is a potentially very significant result - one that can lead to an evolving revolution in the approaches to mine countermeasures both in capability and in cost. As we move from tethered, to teleoperated, to independently programmed vehicles, and finally to truly autonomous systems behaving in ensembles according to rules and/or having self-programming capabilities that permit learning from experience (as in search or in object classification); we reduce the hazardous exposure of humans. Humans will be in-the-loop as control and manual override for the foreseeable future. The approach envisioned captures the promise of technology as a force multiplier.

In the summarizing remarks at the Symposium and again in the Quick Look Summary edition of MINE LINES the emerging set of new mine countermeasures tools, the Autonomous MCM Brigade was introduced. At present this organization is purely conceptual, an objective rather than a present tangible entity. The value of this concept is similar to the utility claimed for being able to identify the bins of the mine countermeasures tool box. The concept permits focus.

Subject to some modifications, the assumption is made that the progression from tethered, through teleoperated, to independent operation, to various degrees of autonomous operation represents the stages of evolutionary acquisition. This , in turn, suggests to the designers of the earlier stage vehicles the necessity of allowing for growth (in capabilities) and making appropriate fit, form, and function reservations for anticipated developments.

The Autonomous MCM Brigade consists of 3 regiments; a land warfare regiment, a naval warfare regiment, and a land civilian-humanitarian regiment. Each regiment has organic air/space squadrons attached. Each type of regiment has appropriate human operated and staffed logistics, maintenance, and operations support personnel. Focus on the hardware organization supported by people rather than the conventional way of describing military organizations in terms of their personnel is intentional as we wish to emphasize the potential operational roles of the autonomous hardware components.

Readers will note that most of the current land warfare mine countermeasures equipment either is or could be configured for combinations of TV scanning and radio control. So could much of the equipment that could be applied to the humanitarian demining mission. The problem there is that cost factors force demining operations into using large numbers of unskilled personnel to conduct mine neutralization and area sanitization operations by hand. Things are less well developed in the naval environments. The Mine Neutralization System is a tethered multi-sensor system operated from the major mine countermeasures platforms. Surface units and aircraft can be teleoperated and radio controlled. Underwater vehicles resembling torpedoes can (and are) programmed to run pre-determined courses and are useful in oceanographic data collection. At present these vehicles do not have hover capabilities.

Whether for land or sea use, the companies (or battalions) of the robotic regiments might be organized to fill specific environmental niches. Greater operational flexibility will be conferred if the sensor/mission packages can be modular so that each vehicle can be efficiently outfitted to perform in the environment at hand. There are competing design approaches. There is a trade off between cost and multiple-capability in a single vehicle. The other extreme is to have a hierarchy of vehicles with each level having greater sensor or mission package capability. It was this latter concept that was envisioned in the introduction to the Autonomous MCM Brigade at the Symposium.

Today, robotic vehicles run the gamut in size from those the size of a cigar box to giant walking machines such as DANTE II. To fix ideas, most of the members of the conceptual Autonomous MCM regiments will be sized between a Standard Gauge Model Train car and a small self-propelled lawnmower. A design principle is to have a total system that degrades gracefully with operational losses rather than catastrophic systems failure that can occur when an irreplaceable unit is lost. costs run from millions of dollars at the high end to as low as 2-5000 dollars for single purpose vehicles (the low end of the hierarchy).

SUGGESTED READING AND REFERENCE

WEAPONS THAT WAIT, Gregory Hartman. Naval Institute Press

"DAMN THE TORPEDOES" - A History of U.S. Navy Mine Countermeasures. Tamara Melia. Office of Naval History

PROCEEDINGS OF THE SYMPOSIUM ON AUTONOMOUS VEHICLES IN MINE COUNTERMEASURES. 1995. Naval Postgraduate School. A. M. Bottoms

CHAPTER 2: OPERATIONAL REQUIREMENTS AND PERSPECTIVES

The Invited Papers in this Chapter are by Senior Military Commanders from the Army, Navy, Marine Corps and Air Force. These papers complement and amplify the Keynote Address by General John J. Sheehan, USMC. Taken together, the papers in Chapters 1 and 2 summarize the needs for operational capabilities.

The ensuing Chapters provide the technical responses to those stated needs.

U.S. Army Initiatives in Mine Warfare

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INTRODUCTION

This January I was summoned to testify before the House Military Appropriations and the House Military Research and Development Subcommittees. On the eve of U.S. peacekeeping operations, the House Members wanted to hear what the services were doing about the frightening prospect of millions of landmines reported in Bosnia. I was part of a panel that gave the congressmen a full description of the different parts of the landmine problem as we saw it. After the presentations, one congressman made the discovery that what "solutions" we had right now--not something in the future, wasn't much different than what we had many years ago-- "You mean after all the money we've spent, all we've really got are probes and coin detectors?" I read your vision statement for this symposium. I'm gratified and encouraged that you are focusing on autonomous systems to counter mines in military contexts. We need to move beyond probes and coin detectors. What I want you ladies and gentlemen to do is to make it an act of great futility for anyone to bury a

container filled with explosives in the earth. I'm thoroughly tired of this seemingly perpetual countermine reactive "catch-up" position. In the very near future, anyone that would bury a container filled with explosives should have the absolute certainty that it will be found and neutralized with little effort and at no operational expense by U.S. ground forces. With detection and neutralization so easy and certain, I'm confident that the threat of the landmine will wither away. I know that finding this "vaccine" won't be easy-- what I am describing is a "silver bullet," - something I told the congressmen did not exist. It doesn't exist today, but I'm convinced that it can. It's my job to frame the requirements for the Army's needs and to work closely with our Marine Corps brethren. We need this effective, low-risk, autonomous system to find and neutralize landmines and I think the academic community has let us down! Over the years, we have fielded isolated pieces of countermine technology, each designed for a specialized application, but not fully integrated into larger solutions. By themselves, they do not contribute to the only two real measures of success I carry in my heart -- mission success,

which means achieving victory and saving lives. You must understand that these are the ultimate requirements and measures of success. I have spent over thirty years in the Army and I have not seen anything, in my time, that would indicate real progress to the larger solutions in this arena and I am extremely frustrated.

And the problem is not only technology integration, part of the problem is how we're organizationally configured to work solutions. There are some silly and counterproductive service turf battles going on centered on the issue of Explosive Ordnance Disposal. The argument goes-- since countermine is an EOD problem, and EOD training belongs to the Navy, therefore the countermine lead is the Navy. The U.S. Navy does a fine job of training EOD specialists from all the services, but the Navy's got a fundamentally different perspective on the operational aspects of land countermine than the services who stand and fight upon the Earth. It makes no sense to ignore the significantly different operational aspects of land and naval mine warfare and to look for

a single set of solutions. This distinction is acknowledged in the seminal text on naval mine warfare, *Weapons That Wait--Mine Warfare in the U.S. Navy*, published by the Naval Institute Press. I bring this up to remind you that, no matter what this symposium is called, there is no all encompassing "mine problem." The challenge of countermine at sea has unique facets and is drastically different from the challenges of land based mine warfare. To solve the land problem, you must become familiar with the environment of land based mine and countermine.

The doctrinal emplacement and operational significance of mines in these two environments is wildly different. Since most of this audience is familiar with Naval doctrine, I'll try to stick to my lane and will only highlight some of the differences as they apply to the land environment, and, indulge me with just a bit of the surf zone. First of all let me demonstrate the state of my understanding of naval mines. If you notice that my understanding of naval mines is imperfect, you can draw similarities with the Navy's understanding of land mines. All I

know about sea mines is that they are large and a single mine incident could result in the loss of a major asset of the United States and the death of many sailors. A single sea mine can have a tremendous operational significance. On land, mines are small, numerous and difficult to detect. Land mines target a vehicle or an individual. Although the psychological impact of a mine strike may be similar, there is comparatively less mission impact from a land mine strike.

When the Navy gets the mission to open a sea lane, that is comparable to the Army's mission of opening a main supply route. The clearance standards are different, as are the ramifications for "missing one." The consequences of a mine strike for the Navy can be the loss of a huge amount of supplies or a major combat element. Consequently, the Navy's goal is to find and neutralize every mine, every time. For the Army, the loss is usually a vehicle. The combat ground commanders are taught to reduce minefield risks to a level commensurate with other battlefield risks. In tactical breaches, conducted under fire, the goal is to remove the bulk of the danger -- which may actually leave some

mines. Unlike naval mines, land mines are usually covered by fire and are only one component of a complex obstacle set. Since the Soldiers are exposed to other lethal threats, speed in the breach is the critical lifesaving parameter.

The largest distinction between land and sea countermine is in the scope of the problem -- the sheer numbers of munitions. The quantity of land mines is staggering. There are over 15,000 minefields in Bosnia alone, and a kilometer of doctrinally emplaced standard minefield can contain up to 3,000 mines. In addition, we have the entire unexploded ordnance or UXO problem with which to contend. Today most munitions are carriers of submunitions--cluster bombs. To give you a feel for the order of magnitude of this problem I will address the UXO's associated with modern artillery. The Multiple Launcher Rocket System is an artillery system that has a dud rate of about 5%. That translates into approximately 34 duds per rocket and upwards of 500 UXOs for a single fire mission! These are unstable UXOs that may detonate if disturbed and we must treat them like mines.

Considering just the land mines, there are two basic types; anti-tank, which attack vehicles, and anti-personnel, which attack individuals. Although it is not an exact comparison, anti-ship and anti-tank mines are similar; the mines are larger, easier to detect and safer to neutralize. Countermine operations at sea do not have an equivalent to the anti-personnel mine found on land. Because of these anti-personnel mines, the problem on land is much more difficult. Anti-personnel mines are deliberately emplaced to complicate countermine operations. They are often employed with hard-to-see trip wires. They are not targeting a system, they are targeting the man who is trying to eliminate an obstacle - and they do a great job. They are small, well-hidden and even once discovered, dangerous to neutralize.

The land force maneuver commander has nine separate countermine tasks, which you will hear about during the week. For the purposes of highlighting differences between land and sea, I would like to focus on just one of these missions; detection. Let me paint a word picture of a typical Soldier conducting a land mine

detection operation under combat conditions. Usually it is night and it is probably cold. Given his tactical environment he probably has what psychologists call, "sleep deprivation" and he's understandably quite scared. He is crawling , because if he stands up, someone may shoot him, and, of course, he must carry the detector equipment with him. He carries a great deal of other equipment on his person at the same time -- typically between 30 and 105 pounds-- the old Army joke is that it's one hundred pounds of ultra-light equipment . . . If the detector covers his ears or blocks his vision, this decreases his ability to react to other battlefield dangers. Finally, if the Soldier misses a mine, he could end up dead. He's tense, the "pucker factor" is high, as we say. To this operational scenario, consider the fact that that the detector does not find all the mines and has a high false alarm rate that can signal on all battlefield clutter. The operator must stay alert to hear all signals. Sometimes when the detector does find a mine, the signal is no more than a click. The Soldier must respond to each alarm. After the Soldier has responded to numerous false alarms, certain human factors kick in. He becomes numbed and

may start to miss signals. We're asking a lot of this youngster! If you've got a teenager at home, consider your son or daughter doing this trade.

By contrast, the Navy countermine solutions are platform based, which allows more sophisticated systems, they are operated by a crew, and they search for larger mines that generate more definitive signals. Land and sea countermine really are two distinct operations who share a last name. If you'll permit an earthy analogy, it's as distinct as the difference between an apple pie and a cow pie.

HUMANITARIAN DEMINING

Mines stay around, polluting the area long after the combatants have gone home. The category of humanitarian demining is mind boggling on land, and relatively unheard of at sea. Professional land forces account for their mines and are bound by laws and ethical standards to remove them, as well as the UXO

hazard they caused; losing forces, however, often fail to do so. Additionally, paramilitary forces, guerrillas, etc. often lay mines indiscriminately. The millions of land mines abandoned in the ground, and their associated risks, almost defy imagination. Humanitarian demining has technical difficulties, political ramifications, public pressure and it is extremely dangerous. This is a difficult mission for the military. It is conducted to extremely demanding standards, established by the U.N. and under a somewhat confusing chain-of-command. We need to tackle this problem systematically and intelligently. One of the stated goals, for this symposium was to: match technologies and systems with the realities of requirements for humanitarian demining. The first step is to expand our thinking. Demining is more than just detect and neutralize - much more! The sub-tasks roughly correspond to the military countermine missions, but because of the setting and scope of the problem, many unique technologies could be applied to execute this mission more effectively. If it should become futile for anyone to bury a container filled with explosives, we can see eventual closure of this humanitarian crisis.

COUNTERMINE TECHNOLOGICAL SOLUTIONS

Remember the Soldier I described trying to detect under adverse conditions? As a result of a great technological breakthrough, the state of the art detector that he might be carrying can actually achieve a 70% detection rate for non-metallic mines. As a senior leader, how am I supposed to direct the employment of this technology? Remember my two measures of effectiveness? Lets examine this technology against mission accomplishment and saving lives. In tests at Fort A.P. Hill this past spring, technicians advanced at a rate of approximately 10 meters per hour - which is much too slow to support a maneuver force. This technology also ultimately endangers my Soldiers, since 30% of the mines are not detected. A suggestion is to put the detector on an unmanned vehicle, which eliminates the risk to the Soldier operator. The undetected mines will either leave a residual risk to the force or possibly detonate under the detector vehicle, returning the force to the hazards of manual detection. A Soldier will philosophically accept a certain amount of risk and even a

Medal of Honor winner will acknowledge fear, but a caring commander will not tolerate an unacceptable risk to both mission and Soldiers. A key point, is that, even on a vehicle, the rate of advance is no greater than a walking pace due to the high false alarm rate. Once again, I'm frustrated.

So we turn to technology to solve the problems and end the frustration. My assessment of the countermine technologies is that they have been, and are continuing to be, developed in laboratory vacuums. We have not broken the code on how to take a promising technology and convert it to a useful system that makes a relevant, fundamental difference. For example, a technology may have a decent probability of detection and a low false alarm rate, but how does that convert to a rate of advance?

For this to work we have to get on the same team. Not just talk about it, but really do it. You need to have a fundamental, holistic understanding of the countermine mission. You need to speak the language we use to describe countermine and the concepts we use to measure mission success. From our perspective many of your performance measures are irrelevant.

For example, probability of detection is really meaningless. I don't need to know how many mines you found, I need to know how many you left. I live in a world that quantifies and deals with residual risk; to do that, I need to know the number of mines that are still present. How do I translate 70% detection into residual risk? Is that probability of detection a result of sensor limitations or statistics? Specifically, will a second pass of this detector result in additional mines being found, and will repeated passes continue to reduce risk. Your performance measures must relate to the maneuver commanders' problems. Would you accept such "operational research-derived" odds if it were your son or daughter operating the equipment? We must understand each other's language.

Another metric you track needs to be converted to "maneuver-speak." The false alarm rate means nothing by itself. I need to know rates of advance. Commanders speak in km/hr, and so must you. You know your equipment better than anyone and are in the best position to "translate" your performance parameters into useful operational measures.

After the performance parameters are translated individually, you must translate the whole system into "maneuver speak" to view its capabilities from the Soldiers' perspective. I will illustrate the confusion between performance measures. Data that describes the latest technology shows the promising characteristics of a 70% probability of detection and a false alarm rate of only one every $30m^2$. When I translate those measures into maneuver speak, it no longer resembles a viable solution. It means I miss 30% of the mines and must stop every 7.5m to investigate a signal. Ultimately you have to ask, does my system really solve the Soldiers' problem?

CHALLENGES

I have shared with you my frustration, I would like to channel your efforts towards specific challenges. This problem is urgent and I desperately need some solutions - some complete operational solutions. These solutions must be workable, they must tolerate mud, dust, rough-handling, corroded batteries, dripping sweat, rain, and humidity. While I don't want to stifle imaginative solutions, this is not a government trough. Your

standard should be your own willingness to take your equipment out into the lethal countermine environment. You need to internalize the idea that your customer is your son or daughter who has to walk through the minefield. Toward this end, I have identified four specific areas where you can focus your attentions:

Employment Concepts:

The first area is that of innovative employment concepts. If the technology is not there yet, I expect you to start thinking "outside the box." When we deployed to Bosnia, we should have been exploring innovative employment concepts to mitigate the technology shortfalls. Instead we continued to pursue "detect and neutralize" technologies. It was Soldier ingenuity that came up with the Panther. This system employs mine rollers on a tele-operated M60 tank chassis. It completely ignores the detect-neutralize do-loop and simply pounds the ground into submission. It uses a throw-away vehicle and takes the Soldier out of harms' way. You know, it is a lot safer and more effective than any of the

detectors in the inventory. I am a strong advocate for the Panther, as it directly contributes to victory and it saves lives.

I know that cutting edge technology is exciting, but perhaps some of the interim solutions lie in innovative applications of existing hardware. If there are combinations or tricks in the employment, I expect you to discover them and share them with the user, such as tilting a detector on its edge to roughly determine the size of the item it's detecting. You know the most about your technology, you need to think about how it can best be employed by Soldiers.

Sensor Fusion:

The second category is that of sensor fusion. This technology has intriguing possibilities, but I have not seen much in the form of a product. To date, efforts to combine or fuse sensors have merely complicated the job of the Soldier. They have relied on the neural system of the Soldier to discriminate between signals and make target determination. Human factors limitations start to dominate the problem. In some cases the Soldier is required to

decipher two differing tones and monitor a heads-up display. The integration of these widely disparate signals is no trivial matter. In the very worst cases, the "fusion" has been a simple link that caused the system to alarm on either sensor. This did little to increase the probability of detection, but nearly doubled the false alarm rate.

Real sensor fusion means one signal. Once the technology is there, you need to consider what is the best way to deliver that signal to the Soldier. Aural signals are subject to interpretation; visual signals are more definitive, but they require the soldier to take his eyes off of the ground. There is a lot of work to be done in this area, but it has a lot of promise. Sensors that are actually fused and intelligently implemented will make the detector more reliable and the Soldiers' job easier and safer.

Humanitarian Demining

The third area I invite you to explore, more fully, is that of humanitarian demining. Although improved detection and neutralization equipment may prove helpful in conducting

humanitarian demining, you need to know that US policy prohibits placing US forces directly in this type of minefield. Your advanced detection equipment will be used by indigenous personnel with widely differing education and motivation levels, in nations with sparse logistical support infrastructure. I think the more lucrative challenge, both operationally and financially, is to devise equipment and coordinated systems to enhance other functions, such as, protection, marking, and training, to name a few. The military is extremely well suited to performing command and control functions, which for demining operations would include: mapping, reporting, recording, maintaining statuses, prioritizing work and disseminating information. We are looking for a data base system that can accomplish these various functions. There is much less emphasis on these support activities. You must grasp this holistic concept before any individual component can really contribute to enhanced mission success.

Standardized Test Beds:

The fourth area, test beds, is a very disturbing issue for me. I continue to be frustrated by tests that show a specific piece of equipment in its most favorable light - regardless of the environment in which it will be employed. Classic examples of this are testing radar systems in dry desert sand, pre-heating target mines prior to tests and sanitizing mine lanes. These methods paint an unrealistic picture of the system capabilities. I need to know how the system will perform in an operational environment. This means testing equipment in all types of weather, various soil types, using representative surrogate targets, in the presence of battlefield clutter, using Soldiers. I strongly support Dr. Kaminski's desire to establish standardized test beds that truly represent operational environments.

Summary:

To summarize, your goal is user satisfaction. The Soldier and Marine, on the ground, are your ultimate customers. The point of marketing, new or existing, technologies is that you have to address an entire operational problem from his perspective and

understand that materiel is only one piece of the puzzle. Quantifying an operational capability, in maneuver terms, in various environments, against various threats is critical. Linking that new technology to a specific employment method, or complementary system may increase its operational value. Finally, you need to test the system in an operational environment that replicates reality. In short, you need to be able to articulate the overall concept of employment, targeting an operational shortfall. I understand that technologies may not meet all of the operational requirements. This situation supports rapid prototyping-typing where the user can contribute to the iterative system improvements. The TRADOC Integrated Concept Team is working together to generate effective requirements. I have a lot of confidence that this team will make great strides in how we articulate user needs. You can count on my continued support in this team effort.

THE POLITICAL ENVIRONMENT

I would like to take a minute to address a related issue. All of us in the mine/countermine community need to be keenly aware of our political environment and have a working knowledge of pertinent policies. As the proponent for land mine warfare, I would like to update you on some critical, recent issues. I am dealing with a large collection of somewhat conflicting laws, rulings, treaties, operational requirements and international sentiment that are driving some difficult decisions on the use of mines. Part of the problem is that each nation has a unique national security strategy. The challenge faced by Iceland is much different than the Republic of Korea.

The players include: the President, Congress, international treaty restrictions and conventions - all, of whom, impact on the mine/countermine employment issues. Through all of this, my focus trying to ensure victory and save Soldier lives.

International sentiment and the President's directive are aimed at reducing the residual risk left by land mines and in the subsequent effects upon the innocents. The U.S. Army employs

munitions that have organic self-destruct or self-neutralizing functions. These munitions accomplish the military functions of encumbering the enemy, both physically and psychologically; while leaving virtually no post-battle residual risk. The self-destruct munitions have come under increased political pressure and are being treated in the same category as non-self-destruct mines. I have a clear understanding of the Commander's intent and the specifics of the Convention on Conventional Weapons agreements. I am now mired in a battle of semantics regarding these other weapons. We must make a clear distinction between self-destruct and non-self-destruct weapons. I cannot speak strongly enough to this issue. The purpose of the current political wave is to eliminate the weapons systems that leave residual, indiscriminate risk to innocents, regardless of whether they are used by a professional or irregular force. We must be intelligent enough to enact our senior leader's guidance as intended.

Perhaps you've never really thought of this, but the fact that we have such a large countermine problem is testimony to the fact that mines are such an effective system. They are emplaced in

large numbers: unfortunately the dumb mines create a residual risk. Supporting this effort to permit the employment of only self-destruct munitions, seeking a solution to the Korean border defense problem, and making headway in demining technologies, are perhaps the three most important things we can do to conquer the humanitarian demining crisis.

CONCLUSION: FINAL CHALLENGE

I've spoken for about thirty minutes and I'm still frustrated. I know this has been a blunt speech - it has been tough to deliver. Despite my sharp frustrations, I am not condemning our countermine efforts. This is a very difficult problem that concerns the entire world. International firms, organizations, industries and governments are dedicating their best talents, and showing little success. I honestly commend your efforts, but I'm also anxious for a product. I cannot ignore the fact that our Soldiers, Marines, Airmen and Sailors are still putting their lives on the line conducting countermine operations. I hope I have made the point that since there is no universality to the naval and land mine

problem, there is no corresponding "mine solution." There may be some overlap in the applications of technologies, but our resources must be channeled into distinctive, user specific solutions. This challenge may take the combined assets of the nation. I realize that some of the financial resources we expected got mired in Congressional and Pentagon bureaucracy. We must get beyond that and forge a strong team, dedicated and resourced in the same magnitude as the "race to the moon." The American public is pumping their hopes and their resources into your solutions. I support your efforts for an extremely productive symposium that results in some tangible gains - - our Soldiers, Marines, Airmen and Sailors are really counting on us.

An Entirely New Approach to the Countermine Mission

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Countermine has become the challenge of the day for the US military and for the world. For too long, too little attention has been paid to this critical battlefield function. Now we are seeing the effects of that neglect, not only in the materiel field, but in everything from a basic problem definition, to force structure implications to a discipline way to approach the challenge, to the terms used to measure success. This briefing will address some of the cutting edge ideas we are exploring to fill these gaps. I hope you will embrace this novel approach and use it as your frame of reference for the remainder of the conference.

With the end of the Cold War, the Army has come to the very real conclusion that countermine has very distinct components. There two primary types of missions. Combat countermine is well understood, as are the terms associated with it. The lexicon really falls short for defining the "other" operation. Terms range from Operations other than War, to Security and Stability Operations. For the purposes of this presentation, I will call them Contingency Operation. These refer to the missions that do not have the same lethal environments as combat and therefore lack the stringent speed requirements. The solutions that meet one mission do not automatically fit the other. For example the requirements for an M1 based breaching vehicle lead us to the Grizzly and the ESMB (a rocket propelled explosive breacher). They are clearly designed for a very narrow mission that does not carry over to the CONOPS arena. This has left operational voids in the missions we are finding the most prevalent. The POM has started to recognize this reality and I find it quite interesting that it does not focus on high intensity conflicts anymore.

The TRADOC Countermine Concept

Within the Army, the Training and Doctrine Command is responsible for defining and formalizing user requirements. The Army has instituted a new process for generating operational requirements. TRADOC is now defining requirements by mission areas. The branch Commandants form Integrated Concept Teams which look at requirements from a holistic perspective - across all of the \Army mission areas. The TRADOC Commander has legitimized this ICT concept by stating that all requirements must be generated or validated by an ICT before he will accept them. As the Commandant of the Engineer School, I have stood up several ICTs, one of them is a countermine ICT.

As you know, countermine is a hot issue in the world today and my Countermine ICT has hit the road running trying to articulate a much needed Army position on future requirements. I will not bore you with all of the action officer level work being done, but we have changed some of the lexicon and you must have a basic understanding of the missions, their sub-missions and components to understand their uniqueness. So please bear with me.

We have gone to great pains to define a base level countermine capability - what it is and what it should be. Clearly every unit must have some organic CM capability, we feel that extends beyond self-protection. The entire military has responsibility for the correct implementation of CM doctrine and use of equipment. When a unit encounters a mine threat, their training, doctrine, and equipment must be employed in response. If the risk is too high they must call for additional CM assets, and there needs to be logical progression in the request protocols. Having the force equipped with sufficient, properly equipped CM response units is proving a challenge.

The problem is bigger than just countermine, it is operations in a mined environment. Mines are a condition of the battlefield and, as such, they influence everything we do. This is not an Engineer problem with Engineer solutions. Every soldier has the potential to step on a mine, every mission has the potential to be complicated by mines, and every piece of equipment has the possibility of encountering mines.

This briefing will highlight the challenges we face and will continue to face in this arena. I will highlight the significant differences between the two countermine operations, combat and CONOPs, and show that they have drastically different requirements. I will more fully explain the components of the countermine mission and finally I will address our vision to more effectively conduct, monitor and evaluate these missions. If we are going to succeed, we need to find and use all of the right tools for the jobs; each job.

B. TWO DISTINCT COUNTERMINE SCENARIOS

The military is coming to grips with the new nature of conflict. In the countermine arena, the differences between combat and contingency operations are significant. I will highlight, from an operational commander's perspective, those key distinctions:

Combat

The combat countermine mission revolves around speed and mobility and the basic components of this mission have not changed much since World War II. The maneuver commander is trying to accomplish his tactical or operational mission and mines are a hindrance. He wants to know where they are, but he doesn't necessarily want to encounter them!

In combat, the commander has many sources of danger to deal with, in addition to the mines, such as lethal fires and fratricide. A commander must make choices that minimize losses and ensure mission accomplishment - sometimes that means being willing to accept a less than perfect breach. The commander must weigh the losses he expects to take crossing a minefield vs. the losses he will take standing still or waiting. Breach methods are fast, violent, destructive, less than complete, but suited to a high paced, combat mission.

Contingency Operations

Countermine CONOPs represent a relatively new mission for the Army - at least in these numbers. Unlike combat operations which are complicated by mines; in CONOPs mines sometimes are the mission! The job is to find them - every single one of them, and neutralize them. As if the problem were not complicated enough, many of the areas are cluttered with UXOs. In a CONOPs situation, they pose a very significant challenge since the mission is to deal with each explosive individually. The standards for clearance are unbelievably high both quantitatively and morally. These areas are potentially future playgrounds for children. These operations are subject to US policy

restrictions which do not allow US soldiers to actually go into the minefields. Our roles are supervisory in nature. We track the minefields, train the trainers, collect intelligence, conduct macro-detection operations, mark dangerous areas, conduct mine awareness training and assist in proofing, to name a few. As you can imagine, collateral damage is a consideration and so the typical combat explosive breach techniques are not usually appropriate.

CONOPs are typically being conducted under the close scrutiny of the State Department, the UN, the American public, CNN or some combination of the above. This gives risk management an unusual qualitative spin. Military officers have been trained to make the hard, but quantitative, judgments regarding mission accomplishment and soldier harm. Now a humanitarian mission, that results in a single casualty can be termed a failure due to public scrutiny and media spin. These intangibles have changed the complexion of the CONOPs countermine mission more than anything else, because they have changed the standards. Although not specifically stated anywhere, the unwritten standard for CONOPs countermine has become "zero-casualties." This poses some extraordinary material and operational challenges.

C. THE NINE COUNTERMINE SUB-TASKS

The two scenarios define the settings in which countermine operations take place, but countermine is not an isolated task, it has many components. The countermine ICT has developed nine mission categories, which is a significant departure from the tasks defined in the previous Army Countermine Modernization Plan. A few of these represent new missions and all of the previous missions now have a broader scope. Finally, the definition and implementation of each of these sub-tasks will be tailored to the specific mission.

I will now briefly review the nine countermine mission areas and highlight their differences as they apply to Combat and CONOPs missions.

Minefield C4I: A new, much expanded, view of minefield intelligence. This includes, but is not limited to all reports, data bases, intel gathering, analysis and dissemination. It involves inputs from and outputs to the entire force and as such must tap into joint C4I nets. It involves people, hardware and software. The desired endstate is to deliver the required CM information, in a usable form, in sufficient time to influence the maneuver commander. The sources, formats, contents and timelines of that information vary drastically between the two missions

a. Combat: Time is essential. Sources of info probably high tech. Need to know where areas are mined (rather than individual mine locations)

b. CONOPS: Accuracy is essential. Sources of intel are largely indigenous people. In order to clear an area, need to know where every mine is located.

Detection: The most difficult and diverse term used in countermine conversations. Detection itself encompasses a vast number of meanings. It can refer to mined areas (are they even using them), minefields (boundaries of dangerous areas) or individual mines (for the purposes of neutralization). Detection can be as technologically sophisticated as an airborne detection platform and as simple as a soldier seeing a trip wire. The primary statistics associated with this task are speed of detection, Pd and FAR. As you might expect, their priorities and requirements vary drastically for the two missions:

a. Combat: The basic question that the maneuver commander asks is "Where can I maneuver most freely?" , i.e. Where are the mines not? The speed of the maneuver force is paramount so fast, accurate detection of mined areas or minefield boundaries drive the requirements train.

b. CONOPS: The laborious task of clearing a country of mines involves needing to find every individual mine. Speed is nice to have, but detection accuracy is more critical. The requirement is to clear to a standard where a playground can be built.

Marking: Simple in principle, sometimes tricky in execution. First of all, several things need to be marked. Minefields, lanes, individual mines, etc. There is no standard for all of these and so there is great confusion. There are a few other distinctions between the two missions:

a. Combat: For marking to be effective, it must be visible to the friendly side and invisible to the enemy. Not to sound like a broken record, but it must go in and be removed quickly, ideally under armor. it must be all weather and durable.

b. CONOPS: The "customer" for these markings are the non-combatants and the deminers. The markings need to be obtuse: visible and understandable by all. One of the interesting problems has been the selection of marking material. These poor countries tend to scavenge anything of value and even simple wooden pickets don't survive.

Breaching:

a. Combat: Speed is the overarching criteria that defines successful combat countermine operations and breaching is the pacing item. In a breach seconds count. Nothing matters more than speed, given that the force can expect to be taking losses from enemy fire while waiting. Albeit reluctantly, Commanders take less than 100% clearance in exchange for speed. The force needs to find fast ways to conduct multiple breaches with higher clearance rates.

b. CONOPS: Largely does not occur. Concerns regarding civilian safety and collateral damage tend to override this. The minor exception would be self-extraction. This would fall into this category because it is the one CONOPs countermine mission where speed dominates the mission success criteria.

Clearing

a. Combat: Even though the clearance standard approaches that of CONOPs, the scope is much less. In combat operations, the military will only clear areas required for valid military purposes.

The scope of the problem is expanded by the legal requirement to conduct Battle Area Clearance (BAC). In accordance with international law, the emplacing force must restore a country to normal by removing the threat from the land contaminated by mines, submunitions, unexploded ordnance, ammunition, missile fuels, weapons and other hazardous debris.

b. CONOPS: This is the bread and butter of a CONOPS mission. Clearing requirements, both in clearance standards and square acreage, define the mission. This

involves the very time consuming task of examining every inch of ground. This is made more frustrating by the policy restrictions that forbid soldiers to enter the minefields. We are limited by the motivation and capabilities of the indigenous population. Their education and competency levels usually fall well below that of the average soldier. Right now we proceed at the rate of PSS-12 and sometimes probes. Solutions that speed up the process seem to either compromise detection rates or are too high tech to be feasible.

Protecting

a. Combat: Protection includes the force, the unit and the individual soldier. Our concept for protection links into intel which warns forces of mine threats. At the unit level it incorporates mine survivability in to all vehicle, weapon systems and building designs. Some of these changes are relatively simple, like not designing passenger seating over tires, or extending the wheel base so that the 60 degree blast cone doesn't take out the driver's legs. This also includes basis of issue items, such as placing rollers on scout vehicles. At the individual soldier level, we are investigating the optimal mix of protective equipment that does not encumber the mission.

b. CONOPS: Protection of our soldiers in a CONOPs situation has many of the same components as in combat. Again, the additional problem in this category are the indigenous people. This includes the "by-stander" type civilians we and the deminers who go into the fields. Although we tend to focus on unconstrained requirements, the realities of operational funding sometimes place our soldiers in some difficult moral decisions where sufficient protection equipment is not available.

Finally, although these operations occur in an ostensibly peaceful environment, often there is lingering hostility and hate. Individual families and organized factions can be expected to deliberately sabotage the countermine efforts.

Neutralization

Neutralization is not a term that clearly understood - or rather everyone has their own definition. It is the act of making an individual mine safe. Here mission focus and success are defined in terms of the individual as opposed to clearance where the standard of measure is an area.

a. Combat: Pat yourselves on the back - this may be one we have mastered. Assuming the mine has been accurately detected, located and isolated; neutralizing it is a relatively simple task and our kit bag is full. It is, of course, a large assumption to think that we can accurately detect, locate and isolate all mines. More often than not, technology limits us from large area neutralization. In an effort to minimize risk, we are looking at methods to neutralizes mines remotely.

b. CONOPs: Because of the collateral damage considerations mentioned earlier, many more mines are neutralized in CONOPs scenarios. Safety, simplicity and prevalence (cost) are the driving factors for the user.

Training

a. Combat: We are exploring a novel approach to training, across the entire force. Countermine needs to be a basic soldier skill, as such it should be taught at basic training and tested annually. Mine awareness should be tailored to specific missions

prior to deployment and updated/reviewed once in theater. Beyond this, though, leaders need to conceptualize mines as a threatening condition of the battlefield. The NBC model is very comparative. Leaders need to learn how to ask and answer the right questions regarding the mine threat - using maneuver language. The goal is to make the presence of mines relevant so that leaders account for them in COA development and selection.

b. CONOPs: Training for CONOPs is a tricky business. The general mine awareness is complicated by the fact that mine types may or may not be known and will probably change as the situation develops and homemade mines are introduced. It is an overwhelming task to catalog the all of the mines, especially when you include the possible UXOs. Since many of the residual minefields are the result of internal conflicts, they are often not laid in any doctrinal pattern. Records of the minefields are also scarce or inaccurate. The ROE for the theater has the potential to complicate countermine operations. The US Army Engineer School is spearheading an effort to expand their countermine training center. Ideally it will address these unique characteristics and send better qualified soldiers into theater.

An entire new category of training is the training of the indigenous personnel. This includes basic mine awareness. There are cultural challenges as simple as language problems and as complex as differing views on the value of life. In many countries, mines have become a way of life - a way of protecting what little personal property they have. If the US efforts are in support of a recent peace accord, resentment and suspicion of the previously warring factions may still linger. Winning the hearts and minds of the population in support of a countermine operation cannot be assumed.

Demining:

a. Combat: Although anything is possible, I do not see this as a combat mission. We may see this after the cessation of hostilities, but that pushes us into a CONOPs scenario.

b. CONOPS: Many of the issues that define this mission have already been touched upon. The technical difficulties of meeting such high standards, coupled with the cultural challenges place this one on the top of the "too hard" list. It is important to mention that the military already performs this mission in a limited capacity. Right now, the Special Operations Forces have the mission. The Army is exploring the best way to expand their support of humanitarian demining. Many of the lessons we have learned while performing CONOPs are proving valuable. International pressure and current administration goals are great motivators to expand this mission, but the Engineers are a limited asset. If the Army takes on this mission, there will have to be some compensatory resourcing, primarily in the form of force structure increases.

CLOSING THOUGHTS:

- Take off your blinders. Your job is much more than making a better mousetrap.

- Combat Countermine and CONOPs countermine are two different animals. We look at them differently, so must you. It's O.K., actually preferable, to design mission specific equipment.

- The mission has much expanded horizontally too. There are nine sub-tasks - not just detect and neutralize.

- We need to speak each others' languages (a dual challenge). Define the value added of your system in operational terms. Pd is dry, sterile and essentially meaningless.

CONOPS

. . . A New Army View

Classic

Countermine

Mission

CONOPS

Countermine

Mission



COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

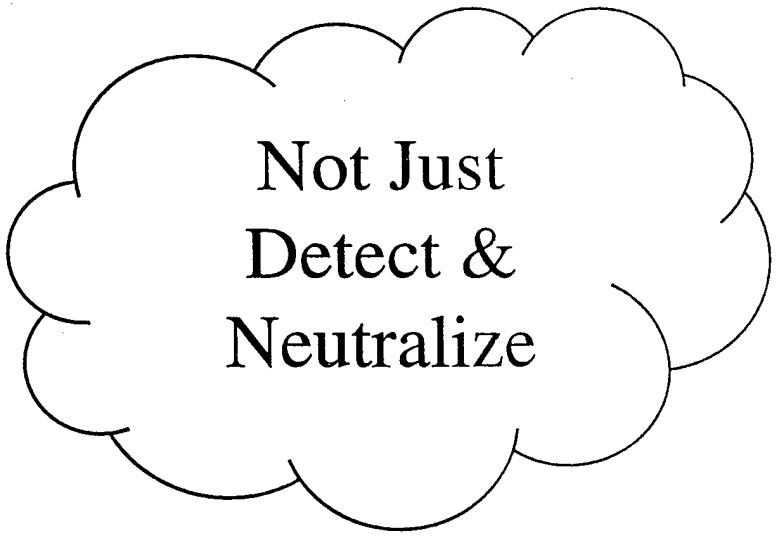
Clearing

Protecting

Neutralizing

Training

Demining



COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

The process of collecting, analyzing, and disseminating intelligence associated with countermine. Prioritizing, controlling, and tracking all countermine missions.

SCENARIO DIFFERENCES
Minefield C4I

COMBAT

- **Time**

CONOPS

- **Accuracy**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

The most critical step in countermine operations. Includes route and area minefield detection, as well as individual mine detection.

SCENARIO DIFFERENCES
Detection

COMBAT

- **Where are there no mines - rapidly, under armor**

CONOPS

- **Where are the mines - time for accuracy**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

An on-the-ground indicator of a mine, minefield, lanes, or by-pass. Must follow established protocols to communicate correct intent.

SCENARIO DIFFERENCES
Marking

COMBAT

- **Mark tactical minefields and lanes for friendly forces - rapidly, under armor**

CONOPS

- **Mark dangerous areas for indigenous personnel - permanent, theft proof**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

A synchronized combined arms operation to project combat power to the far side of an obstacle. Usually executed under enemy fire.

SCENARIO DIFFERENCES
Breaching

COMBAT

- **Speed, speed, speed - usually under enemy fire**

CONOPS

- **Largely does not occur**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

Total elimination or removal of an obstacle. Usually not conducted under fire.

SCENARIO DIFFERENCES
Clearing

COMBAT

- **Only clear areas needed for operations**

CONOPS

- **Only clear areas needed for operations -- May encompass large areas**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

Steps taken to prevent a mine incident or to reduce the severity of a mine incident if it does occur. Categories include: individual, vehicle, and unit protection.

SCENARIO DIFFERENCES
Protecting

COMBAT

- **Includes total force from unit to soldier - Countermine just one of the threats**

CONOPS

- **Protection focuses on mine incidents, more important given political environment**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

When a mine has been rendered incapable of firing.

SCENARIO DIFFERENCES
Neutralization

COMBAT

- **Usually have brute force option**

CONOPS

- **Safety, simplicity, and collateral damage consideration**

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

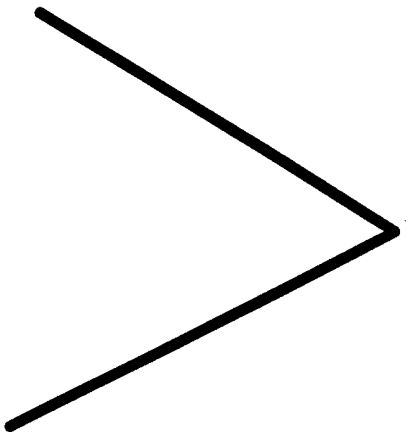
Demining

The process whereby a force prepares itself to perform its assigned missions. Includes entry level, annual, pre-deployment, in-theater; individual and collective skills.

SCENARIO DIFFERENCES
Training

COMBAT

CONOPS



No significant difference

COUNTERMINE MISSION AREAS

Minefield C4I

Detection

Marking

Breaching

Clearing

Protecting

Neutralizing

Training

Demining

Demining is the process of removing all mines and UXOs from a non-combat area. Conducted under various constraints using various assets. Can involve interface with diplomats, contractors, NGOs, and indigenous personnel.

SCENARIO DIFFERENCES
Demining

COMBAT

- **Not occuring during combat**

CONOPS

- **High standards - technical and cultural difficulties - policy restrictions - training challenges**

Regional Insights - Bosnia

Bosnia Mission -- initial requirements!

- Mark minefields -- FWF
- Clear minefields -- FWF
- Proof minefields -- FWF & US*

Clearing Priorities

- IFOR required areas
- Areas to allow freedom of movement
- Areas threatening civilian population

Bosnia Standards

- **Cleared:**

  all mines recorded on FWF minefield recording form have been accounted for.

- **Proofed:**

  minimum of 2 passes over the surface area by a roller at a speed less than or equal to 5 mph

Route Requirements

- Areas proofed 50m each side (300 for MSR)
- Bunkers along routes dismantled
- Wire removed to 50m each side
- UXO removed 50m each side

Bosnia Support

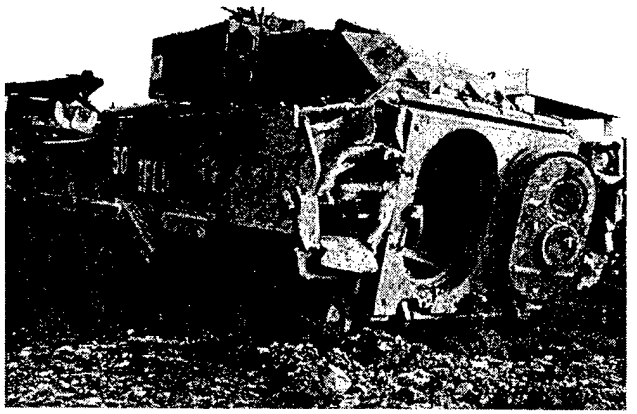
- Mine awareness training package
- Countermine equipment w/training
- Mine-type database

Bosnia Bureaucratic Obstacles

- Army directed to field technology
  - President
  - Joint Congressional Committee
  - Secretary of Defense
  - Chairman of JCS
- Funding still not available!

Bosnia Lessons

Supervising faction clearing:

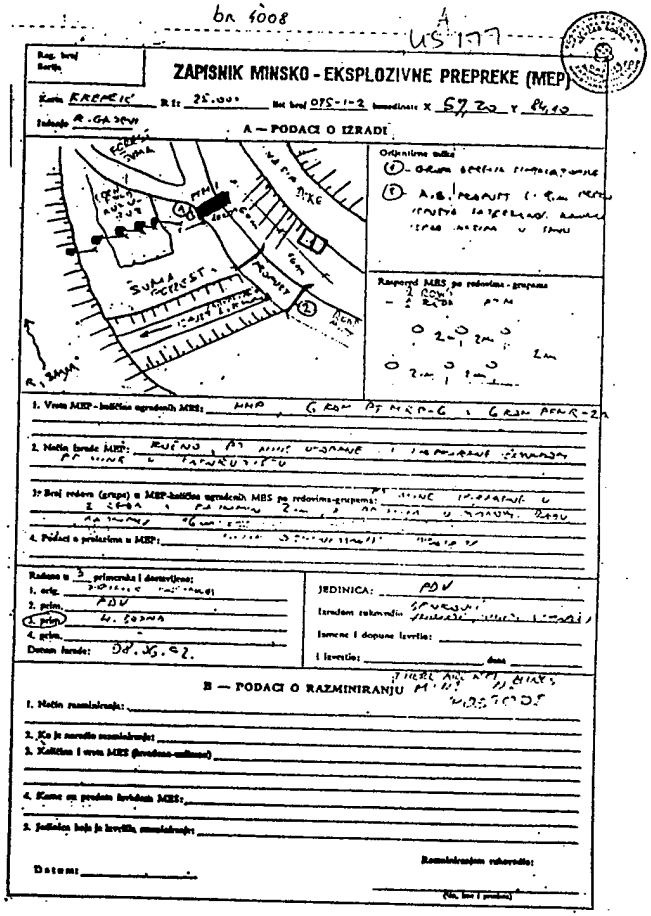


- Cleared doesn't mean cleared!
- Cleared mines must be destroyed

Bosnia Lessons

Countermine Intelligence:

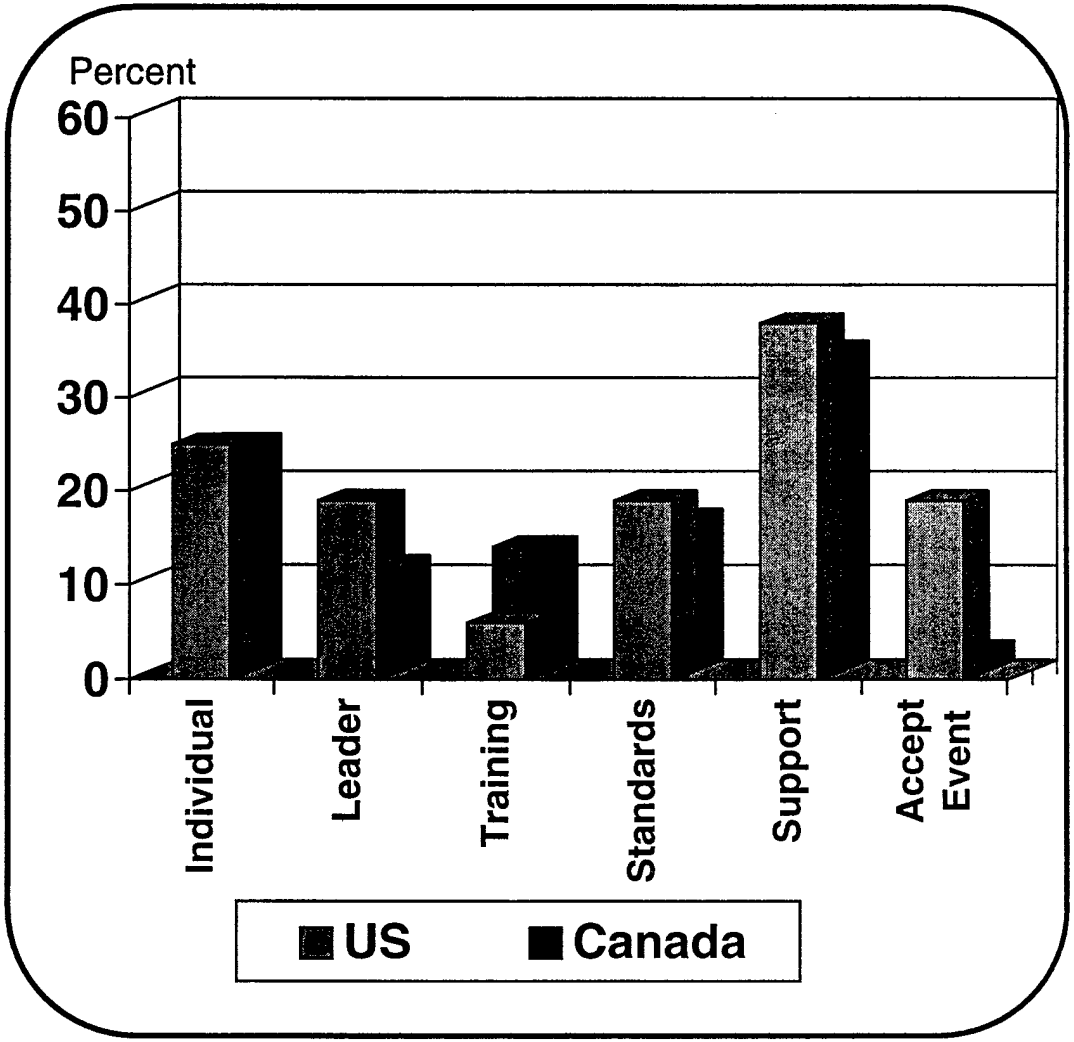
- Poor threat intelligence
- Interesting minefield records
- Mine database critical



Bosnia Lessons

Mine incident analysis:

- Canadian study
- US experience

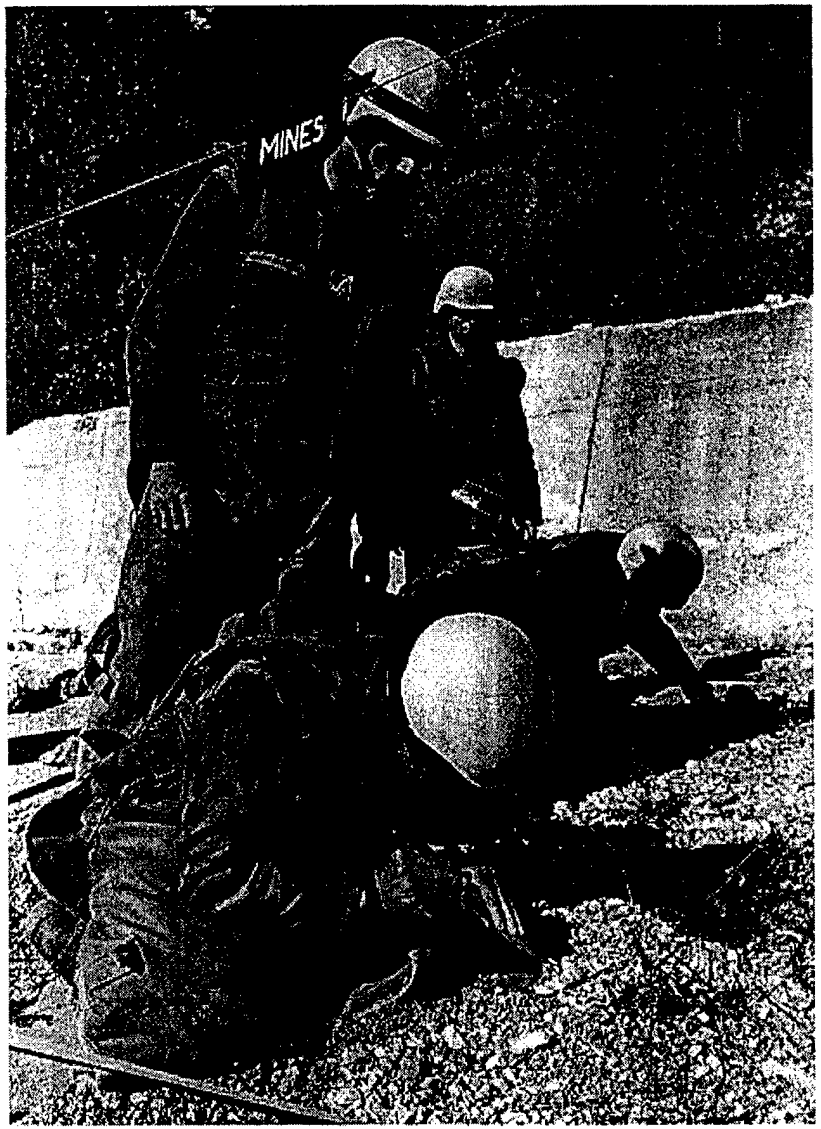


Bosnia Lessons

Detectors of choice:

- Probe
- Dog




MINES

Bosnia Lessons

Detector substitutes of choice:

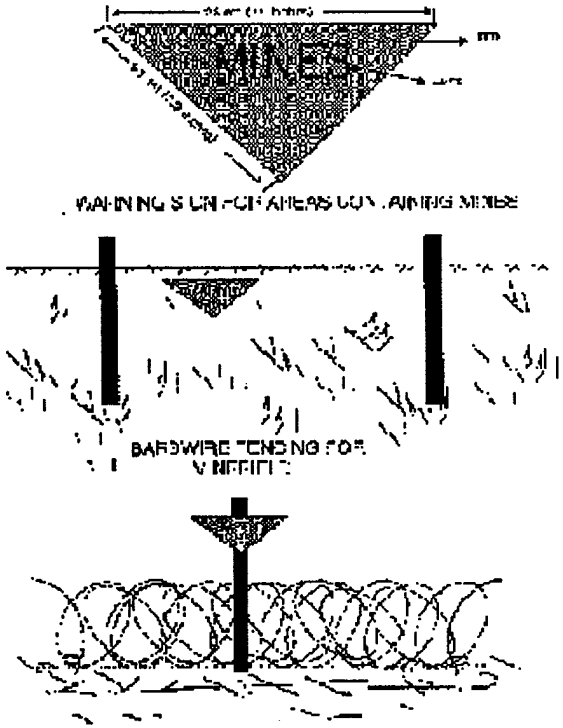
- Panther: detonates pressure fuses, remote control up to 4 km, can bridge ditches and small gaps

- Mini-flail: detonates AP mines, small & lightweight, remote control up to 400 m

Bosnia Lessons

Marking:

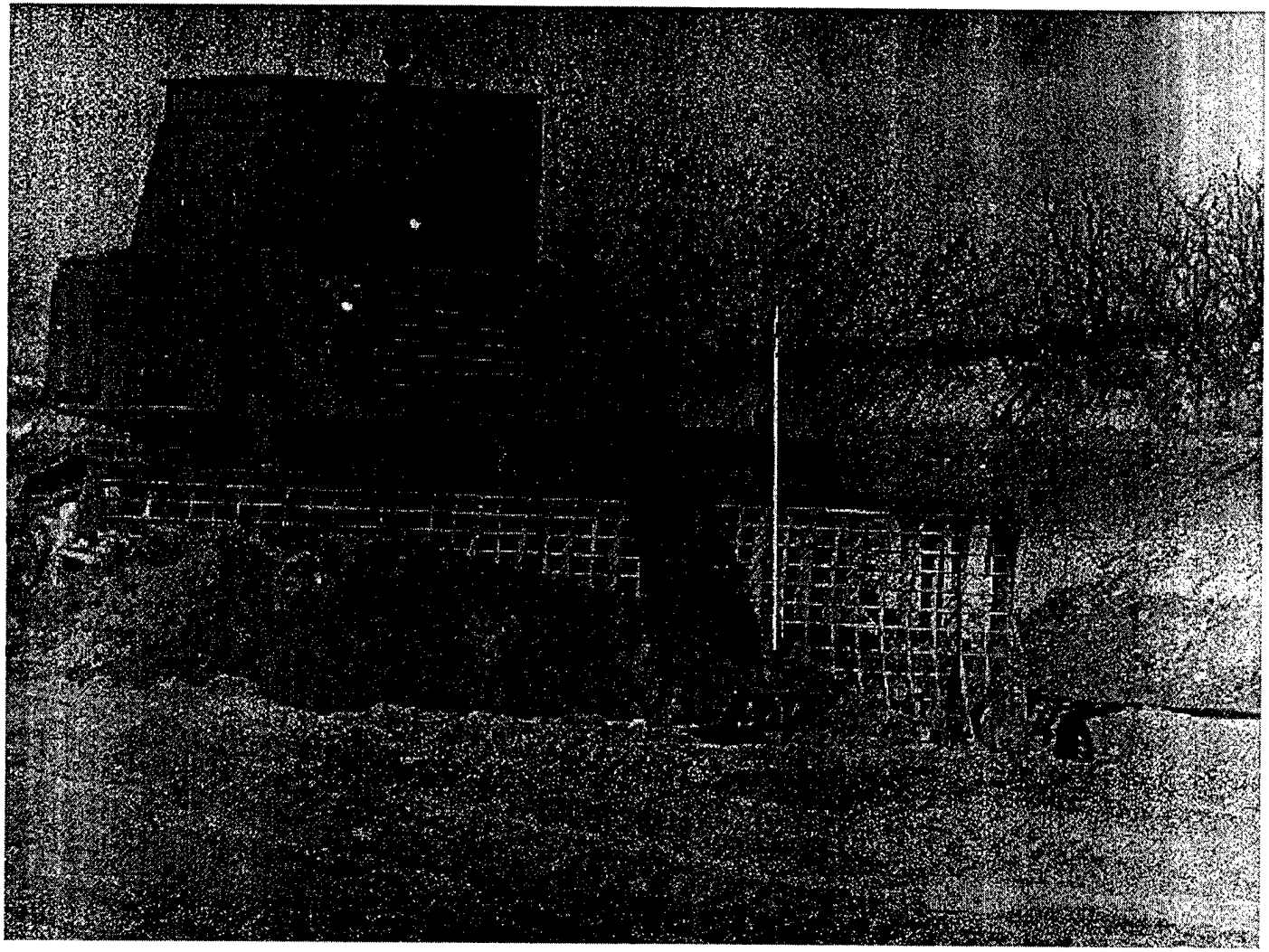
- ?
- Picket driver

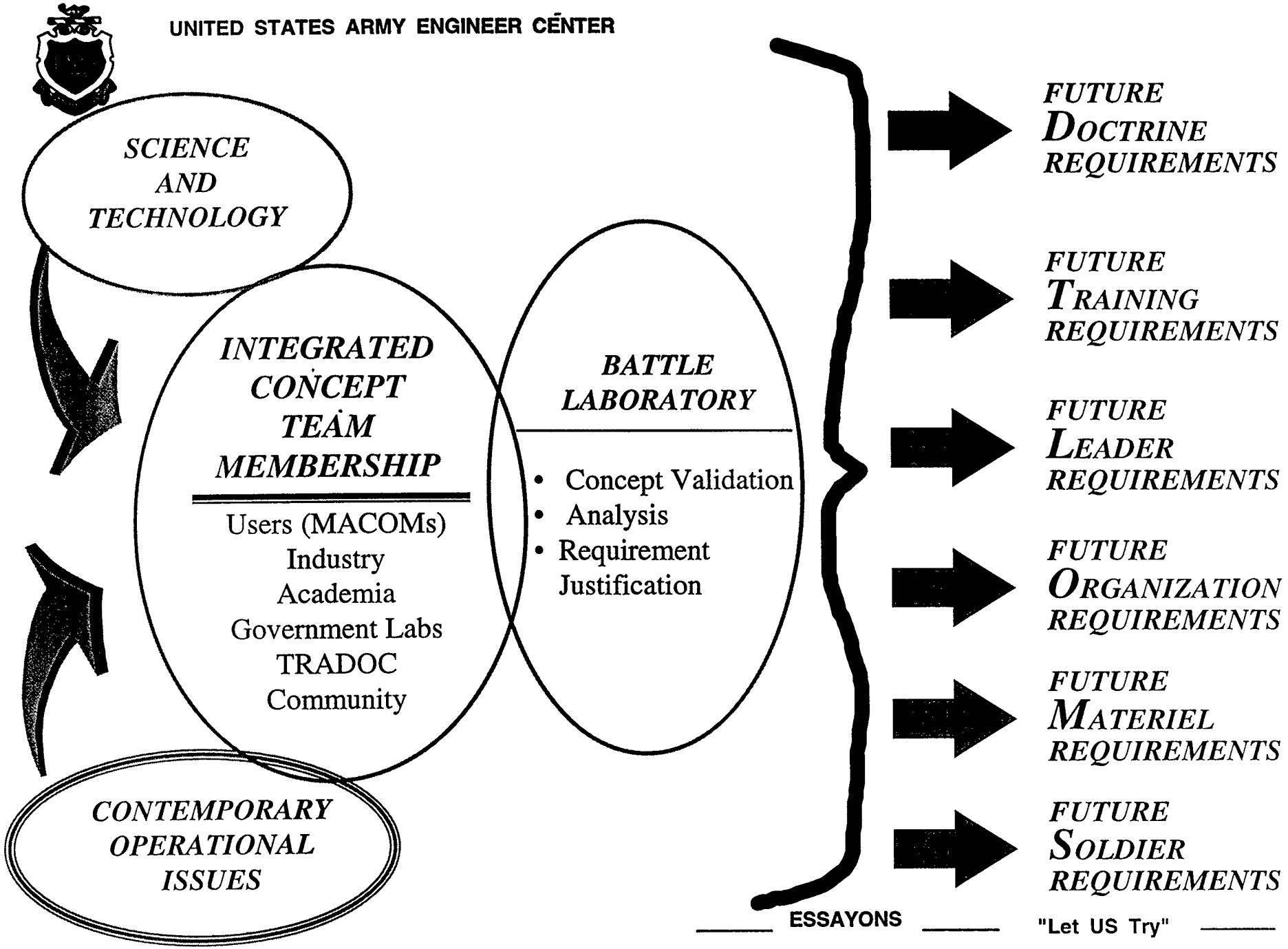


Bosnia Lessons

Mine Protection:

- Bolt-on armor
  - M113 APC
  - HMMWV/5-ton
  - D7 Bulldozer
- Mine resistant vehicles
- BASIC?




SCIENCE AND TECHNOLOGY
INTEGRATED CONCEPT TEAM MEMBERSHIP
Users (MACOMs)
Industry
Academia
Government Labs
TRADOC
Community
BATTLE LABORATORY
• Concept Validation
• Analysis
• Requirement Justification
CONTEMPORARY OPERATIONAL ISSUES
FUTURE DOCTRINE REQUIREMENTS
FUTURE TRAINING REQUIREMENTS
FUTURE LEADER REQUIREMENTS
FUTURE ORGANIZATION REQUIREMENTS
FUTURE MATERIEL REQUIREMENTS
FUTURE SOLDIER REQUIREMENTS

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MISSION	COMBAT	CONOPS
Minefield C4I	Amber (-)	Amber
Detection	RED	RED
Marking	Amber	Green
Breaching	Amber	X
Clearing	RED	RED
Protecting	RED	RED
Neutralizing	Green	Amber
Training	Amber	Amber
Demining	X	Amber

CONOPS Regional Perspective

- Countermine is more than detect & neutralize
- CONOPS is different than combat
- Countermine tools must be mission specific
- No "Silver Bullet"



U.S. Air Force Roles in Mine Warfare

COL Leroy Barnidge, USAF
28th Bombardment Wing Commander,
Ellsworth Air Force Base,
(Personal Representative of
LTGEN Phillip E. Ford, USAF,
Commanding General, U.S. 8th Air Force,
and Air Force Component Commander,
U.S. Atlantic Command)

OVERVIEW

- MINE WARFARE HAS PLAYED A PART IN EVERY MAJOR U.S. CONFLICT AND WILL LIKELY CONTINUE TO DO SO IN THE FUTURE.
- FIRST, I WILL REVIEW SOME MINE WARFARE HISTORY FROM THE REVOLUTIONARY WAR THROUGH DESERT STORM.
- NEXT, I WILL DISCUSS SOME ISSUES CONCERNING MINE WARFARE TODAY.
    - I WILL SHOW THAT ALTHOUGH THERE HAS BEEN A SHIFT IN MISSION EMPHASIS OVER THE LAST FEW YEARS, THE FUNDAMENTAL GOALS OF MINE WARFARE HAVE REMAINED THE SAME.
    - THEN I WILL MENTION AN EXPANDING AREA OF JOINT COOPERATION BETWEEN THE AIR FORCE AND THE NAVY.

- AFTERWARDS, I'LL EXAMINE SOME OF THE ADVANTAGES AND DISADVANTAGES MINE WARFARE BRINGS TO THE WARFIGHTING CINCS.
- FINALLY, I WILL COVER AN EMERGING ROLE FOR THE B-52 IN MINE COUNTERMEASURES AND DEMINING.

HISTORY

- WHAT HAS BEEN THE IMPACT OF MARITIME MINE WARFARE IN U.S. CONFLICTS?
    - MINE WARFARE DATES BACK TO 1777, WHEN DAVID BUSHNELL FIRST SET HIS WATERTIGHT POWDERKEGS ADRIFT IN THE DELAWARE RIVER TO SINK BRITISH WARSHIPS ANCHORED THERE DURING THE REVOLUTIONARY WAR.
    - LATER, DURING THE U.S. CIVIL WAR, THE CONFEDERATE NAVY THOUGH INFERIOR TO THE UNION NAVY, WAS ABLE TO SINK OR DAMAGE 35 UNION SHIPS WITH MINES.
    - IN WORLD WAR I, BOTH SIDES LOST A TOTAL OF APPROXIMATELY 1,000 WARSHIPS AND MERCHANT SHIPS TO SOME OF THE OVER 230,000 MINES LAID.
    - IN WORLD WAR II, THE NUMBERS WERE EVEN GREATER.
        - OVER 2,600 SHIPS SANK OR BECAME DAMAGED BY THE 300,000 MINES LAID

- DURING THE KOREAN CONFLICT, THE NORTH KOREANS USED 1904-VINTAGE RUSSIAN MINES AT WONSAN HARBOR TO IMPEDE U.S. PROGRESS RESULTING IN FOUR U.S. MINESWEEPERS BEING SUNK, AND FOUR DESTROYERS AND ONE FLEET TUG BEING DAMAGED.
    - THIS PROMPTED THE NAVY TO MAKE MINE COUNTERMEASURES A PRIORITY AND IN THE WORDS OF A SENIOR RANKING ADMIRAL, "NO SO-CALLED SUBSIDIARY BRANCH OF THE NAVAL SERVICE, SUCH AS MINE WARFARE SHOULD EVER BE NEGLECTED OR RELEGATED TO A MINOR ROLE IN THE FUTURE."
- DURING THE VIETNAM WAR, IN PERHAPS THE MOST SUCCESSFUL MINING OPERATION, B-52S FROM THE UNITED STATES AIR FORCE'S STRATEGIC AIR COMMAND MINED NORTH VIETNAM'S HAIPHONG HARBOR WITH MK-52S AND APPROXIMATELY 11,000 DESTRUCTOR (DST) MINES.
    - THIS ACTION COMPLETELY STOPPED SHIPPING COMING INTO AND OUT OF THE HARBOR, CUTTING OFF THE FLOW OF EQUIPMENT.

- DURING THE PERSIAN GULF WAR, THE IRAQIS LAID MORE THAN 1,000 MINES OFF THE IRAQI AND KUWAITI COASTS.
    - REQUIRED U.S. AND COALITION FORCES TO CONDUCT SWEEPING AND BREACHING OPERATIONS.
    - BECAUSE U.S. NAVAL FORCES HAD AN INSUFFICIENT AMOUNT OF MINESWEEPING RESOURCES TO CLEAR THE AREA, A HELICOPTER CARRIER AND CRUISER WERE DAMAGED.

MINE WARFARE TODAY

- MINE WARFARE HAS HAD AN ENORMOUS IMPACT DURING NAVAL CONFLICTS OF THE PAST.
- TODAY IN THE POST-COLD WAR ENVIRONMENT, THERE IS A SHIFT IN MISSION EMPHASIS.
    - DURING THE COLD WAR, OUR EMPHASIS FOR MARITIME MINING OPERATIONS WAS TO PREPARE FOR OPEN-OCEAN (BLUE WATER) WARFARE WITH THE SOVIET UNION.

- NOW, THAT SINGULAR THREAT HAS CONSIDERABLY DIMINISHED AND OUR EMPHASIS HAS SHIFTED MORE TOWARDS THE LITTORAL (BROWN WATER) ARENA.
- HOWEVER, DESPITE THE CHANGE, THE FUNDAMENTAL GOALS OF MARITIME MINE WARFARE CONTINUE TO BE BASICALLY THE SAME:
    - DENY THE ENEMY USE OF DESIGNATED OCEAN AREAS, PORTS OR WATERWAYS.
    - RESTRICT THE MOVEMENT OF ENEMY FORCES BY CHANNELING OR DESTROYING ENEMY SHIPPING.
    - ESTABLISH AND MAINTAIN BLOCKADES.
    - KEEP FRIENDLY SEA LINES OF COMMUNICATION OPEN.
    - REDUCE THE ENEMY NAVAL THREAT IN OUR CARRIER BATTLE GROUP OPERATING AREAS.
- CURRENTLY, THE AIR FORCE'S SOLE MARITIME MINING ASSET IS THE B-52 STRATOFORTRESS. THE B-52 OFFERS:
    - LONG RANGE—UNREFUELED COMBAT RADIUS IN EXCESS OF 5,000 MILES

- PRECISION STRIKE CAPABILITY—UTILIZING THE GLOBAL POSITIONING SYSTEM
- LARGE PAYLOAD
  - CARRIES UP TO 51 DST OR QUICKSTRIKE MINES
  - CARRIES UP TO 18 MK-60 MINES—THE NAVY'S MOST SOPHISTICATED ANTI-SUBMARINE WARFARE MINE
- QUICK RESPONSE TIME—MINES CAN BE LAID ANYWHERE IN THE WORLD IN 24 HOURS
- ABILITY TO RESEED A SWEPT MINEFIELD IN A MATTER OF HOURS

- MARITIME MINING OPERATIONS ARE MORE THAN SINGLE SERVICE'S RESPONSIBILITY—THEY REQUIRE A JOINT EFFORT.
  - A MEMORANDUM OF AGREEMENT (MOA) BETWEEN THE AIR FORCE AND NAVY CONCERNING MARITIME OPERATIONS IS BEING UPDATED TO BETTER REFLECT THE NEEDS OF BOTH SERVICES FOR JOINT MARITIME OPERATIONS IN A WARTIME ENVIRONMENT.
  - IN ADDITION, A TRAINING MOA IS ALSO BEING DEVELOPED TO ALLOCATE TRAINING TIME AND FUNDS TO FACILITATE JOINT

TRAINING AND TO FAMILIARIZE EACH SERVICE WITH THE OTHERS' STRENGTHS AND LIMITATIONS.

HOW DOES MINE WARFARE AFFECT THE WARFIGHTING CINCS?

- IT BRINGS THE WARFIGHTING CINCS SEVERAL ADVANTAGES:
  - FIRST, A DEVASTATING PSYCHOLOGICAL IMPACT THAT CAN QUICKLY ERODE ENEMY MORALE.
  - SECOND, JUST IMPLYING A MINEFIELD EXISTS IS OFTEN ENOUGH TO REROUTE FORCES OR SLOW AN ADVANCE.
  - THIRD, MINES ARE A RELATIVELY INEXPENSIVE METHOD OF RESISTING A MUCH LARGER FORCE OR PROVIDING AN IMPENETRABLE BARRIER.
  - FOURTH, NEWER U.S. MINES ARE SAFER TO USE BECAUSE THEY SELF-STERILIZE AFTER A PREDETERMINED AMOUNT OF TIME.
- ON THE OTHER HAND, MINES ALSO HAVE SEVERAL DISADVANTAGES.
  - MINEFIELDS MUST BE SWEPT AT THE END OF HOSTILITIES.
    - WE MUST COMPLETELY CLEAR ANY MINEFIELD SOWN SO THAT IT WILL NO LONGER BE A RISK.

- SELF-DESTRUCT DEVICES MUST BE USED WHENEVER POSSIBLE TO LIMIT THE TIME OF AN ACTIVE MINEFIELD.

- IN ADDITION, OLDER MINES MAY BE AS DANGEROUS TO FRIENDLY FORCES AS THE ENEMY.
  - WE CANNOT BE 100 PERCENT CERTAIN WE HAVE FULLY CLEARED A MINEFIELD.
  - TODAY, INDIVIDUALS ARE STILL BEING KILLED OR INJURED AROUND THE WORLD FROM MINES NOT CLEARED FROM PREVIOUS CONFLICTS.
- FINALLY, THE INTERNATIONAL COMMUNITY TENDS TO LOOK UNFAVORABLY UPON MINES.
  - MINES WAIT FOR THEIR TARGETS TO PASS BY AND ATTACK FRIEND AND FOE ALIKE.
  - THE ISSUE OF BANNING LAND MINES HAS BEEN AN ONGOING TOPIC IN THE NEWS THIS PAST YEAR.

MINE COUNTERMEASURES/DEMINING

- AN EMERGING MISSION FOR THE AIR FORCE IN MINE COUNTERMEASURES AND DEMINING IS USING THE B-52 TO DELIVER

LARGE AMOUNTS OF ORDNANCE ON KNOWN MINEFIELDS TO DEMINE THEM.

- THIS MISSION WAS ATTEMPTED IN OPERATION DESERT STORM, MOST NOTABLY THE MINEFIELD BREACHING MISSIONS IN IRAQ AND KUWAIT.
- HOWEVER, THE AIR FORCE POSITION IS THAT EMPLOYING THE B-52 IN THIS MANNER PRODUCES LIMITED RESULTS.
  - FIRST, WE CANNOT ASSUME THAT SIMPLY RELEASING ORDNANCE ONTO AN ACTIVE MINEFIELD WILL SAFELY CLEAR A CORRIDOR.
  - SECOND, THERE IS NO GUARANTEE THAT ALL MINES WILL HIGH ORDER DETONATE UPON RELEASE OF WEAPONS.
  - THIRD, BREACHING OR DEMINING OPERATIONS TAKE OUR LIMITED NUMBER OF B-52S AWAY FROM OFFENSIVE OPERATIONS WHEN EMPLOYED ON A LARGE SCALE.
- WE NEED TO STUDY OF THIS TYPE OF DEMINING FURTHER TO MAKE A MORE INFORMED DECISION ON ITS EFFECTIVENESS.

- OUR PRESENT PRIORITIES SHOULD BE TO IMPROVE CURRENT METHODS OF SWEEPING, BREACHING AND DEMINING.
- HOWEVER, WE SHOULD CONSIDER ALL FEASIBLE MEANS TO ACCOMPLISH THIS MISSION WHEN TRADITIONAL METHODS ARE UNAVAILABLE.

CONCLUSION

- MINE WARFARE IS A TREMENDOUS ASSET TO WARFIGHTING.
  - WE HAVE USED MINES IN CONFLICTS FOR OVER 200 YEARS AND WILL PROBABLY DO SO FOR YEARS TO COME.
  - MINES AND MINEFIELDS USED CORRECTLY AND RESPONSIBLY AFFORD MINIMAL RISK TO THE OWNER YET PROVIDE AN IMPOSING DETERRENT TO AN ADVERSARY.

Technology
and the Mine Problem

LTGEN Jefferson Davis Howell, Jr., USMC
Commanding General, Marine Forces Pacific
(MARFORPAC)

Good morning Professor Bottoms and distinguished experts. I appreciate the opportunity to speak with you today, especially after having discussed mine warfare with Professor Bottoms. I am really confident we are headed in the right direction when mine warfare is addressed at such a high level and in such a prestigious setting as the U. S. Naval Postgraduate School. This conference symbolizes a recognition that mine warfare is truly a Navy-Marine Corps problem that needs to be seriously addressed. With today's drawdown of forces, fewer forward bases, and fewer forward deployed forces our country is increasingly reliant on the Navy-Marine Corps team's ability to operate forward, from the sea. Mine warfare affects both the Navy and Marine Corps because it directly impacts our ability to project power through naval warfare.

I think Sir John Fisher, Great Britain's First Sealord during World War I, captured the key to success in naval warfare when he said, "The whole principle of naval fighting is to be free to go anywhere with every dammed thing the Navy possesses."

Unfortunately, at a relatively low cost to our enemies, mine warfare can seriously interfere with our uncontested control of the sea and freedom of maneuver.

While this low cost weapon, available to nearly any nation, can challenge our uncontested control of the sea and freedom of maneuver, it is not an inpenetrable barrier. Reflecting on the USS TRIPOLI and USS PRINCETON incidents in the Arabian Gulf, we find that both these ships operated un-knowingly in the midst of a minefield for two days with no adverse effect. The mines were effective, however, as no amphibious landing took place in Kuwait due in part to the risk of troop carriers and landing craft being lost to mines. The potential physical destruction to our assault forces from mines was simply too great.

Another example of the effectiveness of mines etched deep in the history of amphibious warfare is our attempt to land in Wonsan during the Korean Conflict in 1952. The North Koreans were able to delay the amphibious landing by almost a week using antiquated Soviet mines. Even the nine days we allowed for mine countermeasures proved insufficient, despite the assistance of eight Japanese minesweepers. After two U. S. and one South Korean minesweeper were lost, the amphibious landing took place only after Wonsan was seized by ground forces. Rear Admiral Smith, the commander of the amphibious task force, wrote in frustration:

> **"We have lost control of the seas to a nation without a navy, using pre-World War I weapons, laid by vessels that were utilized at the time of the birth of Christ."**

Although I know a lot of effort has been put into mine warfare and mine countermeasures since the Korean War and even more so since the Gulf War, we still do not have a satisfactory solution to this problem. Countermine warfare continues to evolve as does amphibious doctrine. Since mine warfare is an ongoing effort that affects many of you in this room, I would like to share some of my concerns about mine warfare and how they affect the way Marine Forces operate both now and in the future.

The Pacific Basin and Southwest Asia are the areas my warfighters operate in. These areas are characterized by vast distances between islands and continents--nations and population centers--separated by water.

As you can see from the chart, the Pacific Theater of Operations covers a large part of the world. **(CHART OF PTO SHOWS SEA LANES IN PACIFIC THEN CENTCOM)**

To put the Central Command Area of Operations in perspective, consider that the AOR takes up an area the size of the United States. In that AOR, two choke points in the sea lines of communication -- the Suez Canal and the Strait of Hormuz -- are vital to the health of the world's economy.

Sea lanes link the oil resources contained in the Central Command area of responsibility with the expanding economies of the Pacific Theater of Operations.

These lines of communication run through an area of the world with a long history of turmoil and strife. Both Southwest Asia and the Pacific-Indian Ocean Basins are plagued by historic animosities, population growth, weapons of mass destruction and illegal drug trafficking. In addition, rapidly developing industrial manufacturing and export capabilities in these countries furthers their need for Mideast sourced petroleum to fuel a growing economy.

Keeping these sea lanes open and maintaining security highlights the need for an amphibious force strong enough and able to maneuver throughout the region. Any naval campaign intended to keep critical SLOCs open will require a landing force. My Marines need to be able to operate from the sea -- from over the horizon up to 200 nautical miles inland. Because we operate on both sea and land, Marines are affected by the entire spectrum of mines; deep water, shallow water, very shallow water, and landmines. Very shallow water mines, those in 10 to 40 feet of water and the surf zone, are probably the most serious and most difficult challenge we face.

The primary effect sought by laying mines is to shape the battlefield to the enemy's disadvantage. The image of a landing craft being heaved in the air by a huge blast probably played itself out in the mind of just about anyone who has ever landed onto a hostile shore. However, as spectacular and sensational as this image is, the physical destruction of ships and landing craft is not the primary desired effect of mines. In amphibious warfare, mines serve to force an advancing opponent to move in a disadvantageous manner. This may mean forcing a landing away from a good landing beach or steering it into an area where it can be counterattacked or attacked by pre-planned fires.

Even with an amphibious doctrine that uses speed and maximum flexibility to allow us to pass over or around enemy minefields using the Operational Maneuver From The Sea Concept or OMFTS, we still need to have a way to clear mines. In the two areas we are most likely to be employed in major regional contingencies, Kuwait and Korea, suitable landing beaches, even with air cushioned landing craft, are limited. The enemy knows where these beaches are, and has plans to defend them either physically or through the use of denial by mines. Even if we have tactical vehicles and utilize dispersion and precision navigation as defined by OMFTS, some mine clearing will be required. The entire concept of OMFTS is to hit the enemy by surprise from beyond the horizon. Mine clearing is not an evolution we can start well in advance of the assault if we want to maintain our surprise.

The assault echelon-- the trigger pullers--can use tactics and limited mine clearing to counter the mine threat. For the follow-on echelon , the echelon that is going to sustain the assault echelon with fuel, ammo, and food it is a different story. Sustainment comes in bulk. Shipping used to transport sustainment materiel isn't compartmentalized and to achieve efficiency can't be dispersed. One or two landing craft in the assault echelon going off course or falling prey to more sophisticated mines that escape our detection efforts may be operationally acceptable; the battle won't be lost. On the other hand, if one or two ships carrying critical supplies from the follow-on echelon get destroyed, we can lose the entire naval campaign. Even though Marines can get a force ashore, if I can't sustain it, I can't employ it. The mines will have achieved their desired effect.

Even in a relatively benign environment, mine warfare affects our ability to project power. As many of you know we are going away from forward bases and are becoming increasingly reliant on maritime prepositioned ships or MPS. Under the MPS concept, the Marine Corps maintains three squadrons of four to five ships. Each squadron of ships carries enough ammunition, logistical support and combat equipment to sustain a 17,000 Marine force for thirty days. The ships pull into a benign port and offload their supplies and equipment while the Marines fly into a nearby airfield. During the Gulf War, we successfully offloaded all three squadrons of MPF ships. Had the Iraqis mined the Strait of Hormuz instead of or in addition to the coastline off Kuwait, we would have faced an entirely different scenario.

Whether moving our MPS squadrons to an area in conflict, moving our naval forces into position for battle or protection of sea lanes, or launching our Marines ashore, we need to know the water is clear. Or we need to make it clear.

Once ashore, Marines face the threat of landmines. The desired effect of landmines is no different from those in the sea. I don't envision losing mass formations of armor to landmines. What I do see is landmines delaying formations long enough so the enemy can engage with other weapons. This could range from antitank weapons to artillery, or even chemical weapons. On today's modern battlefield, the effects of fires are far more lethal than those of previous wars, even more so against a stationary target. Compounding the problem, in places such as Korea, the terrain is so restrictive that a temporarily halted force quickly becomes a lucrative target with no place to disperse.

Even in operations that don't constitute major regional contingencies, mines pose a challenge. In Military Operations Other Than War or MOOTW, in which we recently provided humanitarian assistance in places such as Somalia and Bosnia-Herzagovina, the disturbing trend

is the casualties we sustain are increasingly from mines. One legacy of the conflicts we face in the Pacific region is the proliferation of leftover mines. Millions of mines are scattered throughout Vietnam, Cambodia, Laos, Iraq, and Korea. The historical and continual use of mines presents us with challenges that now are receiving attention. Over the last five years, Marines have been involved in humanitarian demining missions in Laos and Cambodia. We are just beginning to tackle the overwhelming task of clearing mines from former areas of conflict. But it is a concern we all share, and we are trying to do something about.

So how do we deal with this challenge? From an operational perspective, we cannot rely on any one system. No matter what countermeasure we come up with, someone will come up with a counter to our counter. Also, we can't just rely on technology alone. We need to integrate technology into our tactics and techniques. If we reduce the threat of mines through technology we lower our risk. If we develop our tactics to counter the threat, we reduce our risk some more. The two measures combined reduce our risk to an overall acceptable level.

Probably the most important thing technology can provide for us is accurate and reliable detection. If we can accurately detect mines, then we have options. We can detect and avoid or we can detect and clear. I can't over-emphasize the word, "reliable". Psychologically, we need to be confident that we know what is out there. This is no small task. In the Arabian Gulf, the water is shallow enough to make bottom influence mines effective while the muddy bottom makes them increasingly difficult to detect. In North Korea, a country that chooses guns over butter every time, sophisticated rising mines, new technology, and clandestine mine sowing methods make detection a continually changing challenge.

Once detected, mines can be avoided. With the increased availability of Global Positioning Satellite receiver equipment, every landing craft, vehicle, and individual Marine can conceivably navigate through narrow mine free corridors.

Technology will also play a part in the other option, detect and clear. We can no longer rely on minesweeping technology that takes weeks to complete. The trend in modern warfare is towards shorter not longer conflicts. Our amphibious doctrine relies on speed and surprise. Even a couple of hours preparation time may be compromising our surprise. We need to develop an instride capability to reliably breach even the most sophisticated minefields whether they be in shallow water, very shallow water, the surf zone or on land.

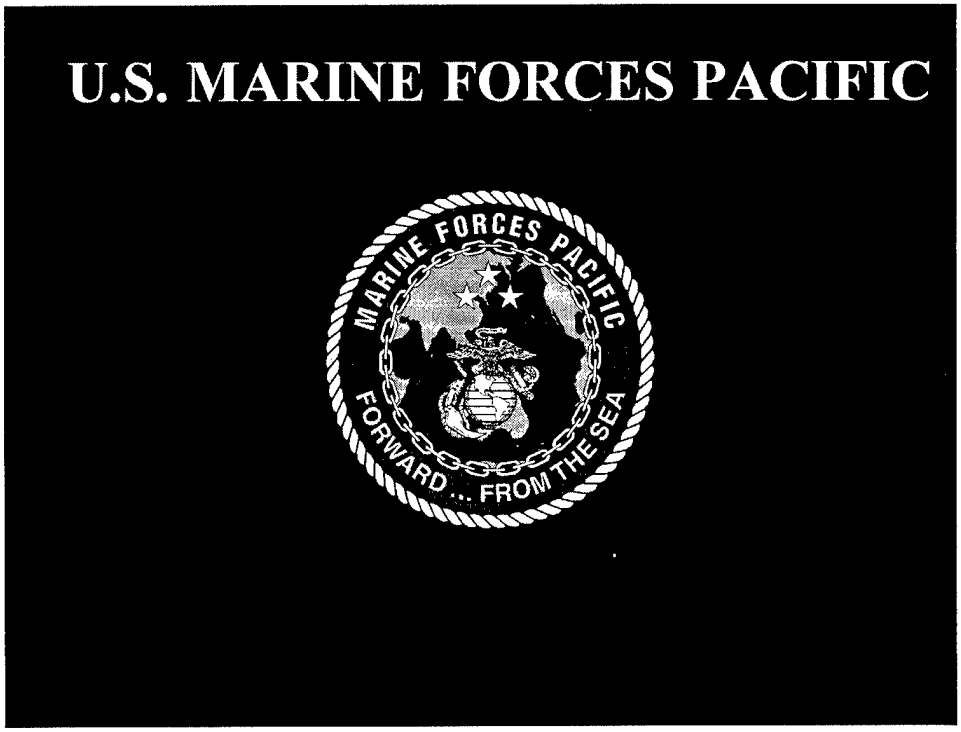
We also need to work on clandestine means of clearing. We learned before long before Desert Storm that we needed a night vision goggles capability to complement helicopter minesweeping. Unfortunately, when Desert Storm came around we still had not developed this capability. Clandestine mine detection and clearing needs to extend into the surf zone. We need to be able to pick our beaches -- not let the enemy pick them for us. Operational Maneuver From the Sea demands that to maintain the advantages of surprise and maneuver, we must develop and enhance our clandestine and covert reconnaissance, clandestine mine clearing, amphibious maneuverability, and in-stride breaching capabilities.

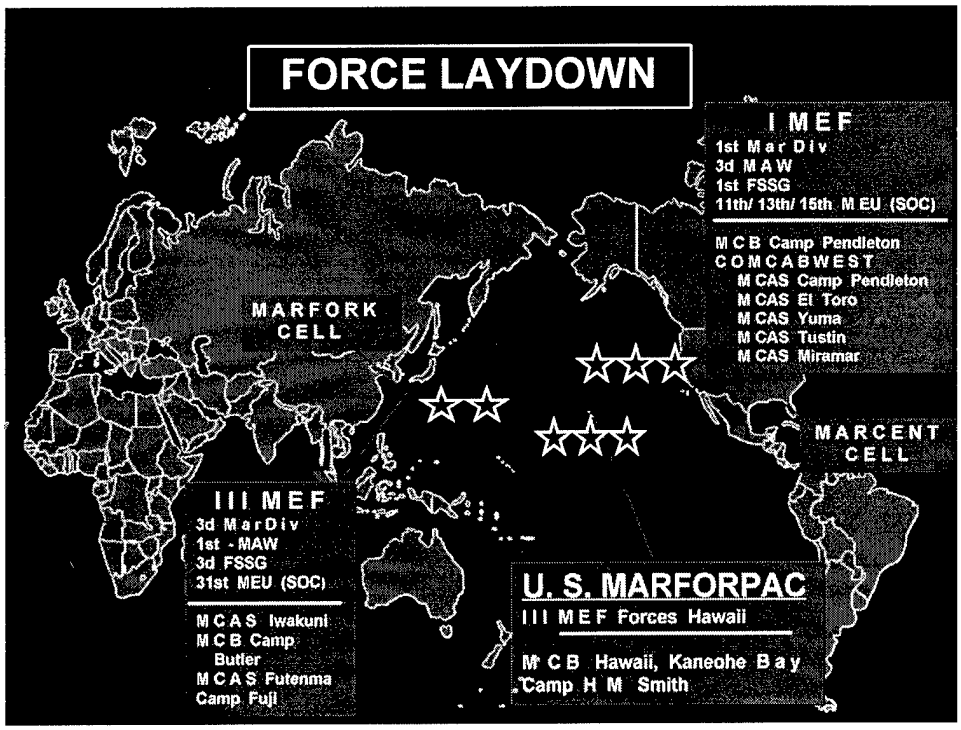
Finally, whatever mine countermeasures we come up with, the equipment has to be immediately available and deployable. We can't afford to give up scarce amphibious platforms to be used as mine countermeasure platforms. Specialized equipment can't be so bulky that there is no room for the trigger pullers. Also, we can't relegate the mine countermeasures mission to the reserves who will never work with naval expeditionary forces until there is a crisis. Mine countermeasure forces need to be integrated and worked into our peacetime exercises. We can't put off mine countermeasures until we go to war again.

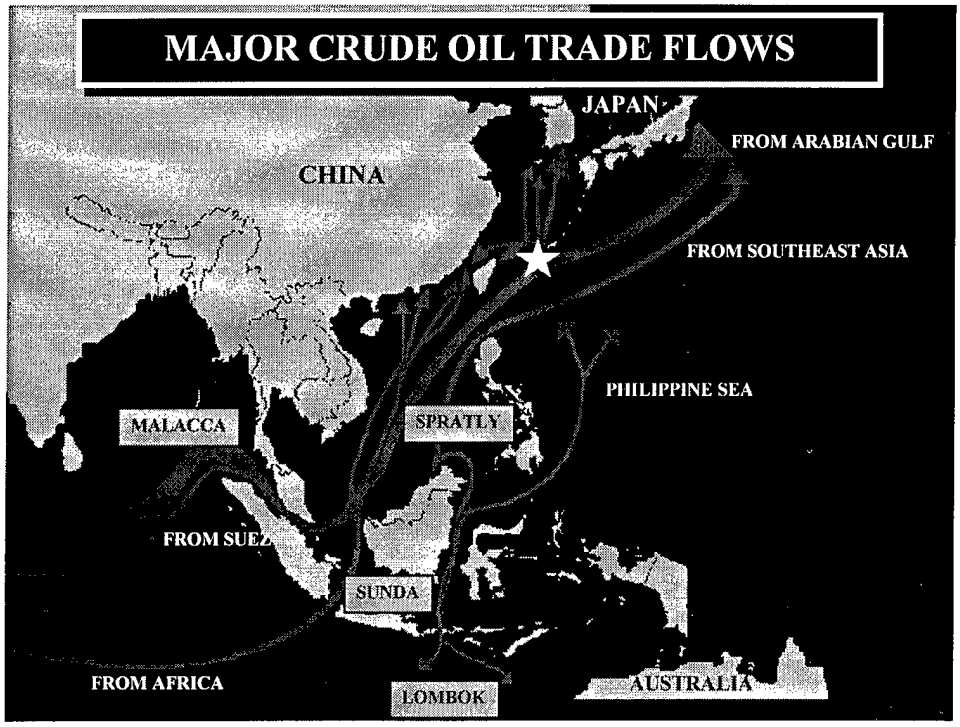
The lesson from Desert Storm, from Korea, from Vietnam is not that minefields are impenetrable. The true lesson is that if we ignore the threat, we will pay for it.

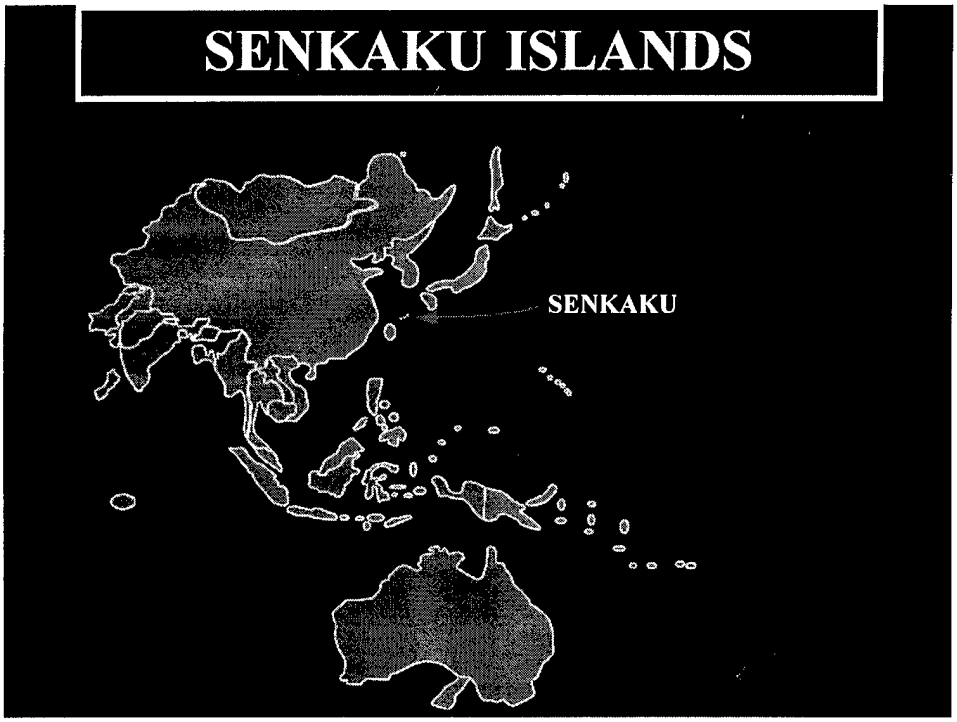
Your work is important to the future operational success of your Marine Corps. Fighting forward from the sea takes courage, tenacity and aggressiveness. Much of that comes in knowing where the mines and obstacles are and eliminating them.

U.S. MARINE FORCES PACIFIC






MAJOR CRUDE OIL TRADE FLOWS
JAPAN
FROM ARABIAN GULF
CHINA
FROM SOUTHEAST ASIA
PHILIPPINE SEA
MALACCA
SPRATLY
FROM SUEZ
SUNDA
FROM AFRICA
LOMBOK
AUSTRALIA


SENKAKU ISLANDS
SENKAKU

The Present and Future of Mine Warfare

RADM Dennis R. Conley, USN
Deputy Director of Expeditionary Warfare (Outgoing)
and Commander, Mine Warfare Command*

GOOD AFTERNOON LTGEN HOWELL, PROFESSOR BOTTOMS, FELLOW FLAG - GENERAL OFFICERS AND SES, LADIES AND GENTLEMEN, TOO MANY DISTINGUISH PEOPLE PRESENT TO RECOGNIZE INDIVIDUALLY, HOWEVER, I WOULD LIKE TO MAKE NOTE OF THE PRESENCE OF THREE FORMER CWMC'S:

IT IS NICE TO RETURN TO NAVPGSCHOL MONTEREY AND ADDRESS YOU AS THE NEW COMINEWARCOM. ..... AT THE OUTSET OF MY REMARKS I WOULD LIKE TO RECOGNIZE PROFESSOR AL BOTTOMS NOT ONLY FOR HIS TERRIFIC JOB IN SETTING UP THIS SYMPOSIUM ..... BUT AS WELL FOR HIS ABSOLUTELY SUPERB CONTRIBUTION TO MIW THROUGHOUT

* RADM Conley was introduced by RADM Herbert C. Kaler, USN, PEO Mine Warfare (P), who was introduced by RADM Richard D. Williams III, USN, PEO Mine Warfare.

HIS TENURE IN THE ELLIS A. JOHNSON CHAIR OF MINE WARFARE. (AL - WE SALUTE YOUR EFFORTS)

I AM DELIGHTED TO PROVIDE YOU A STATUS OF MINE WARFARE FROM THE FLEET PERSPECTIVE DURING THIS FIRST DAY OF THE SYMPOSIUM. ....THE YEARS WHICH HAVE PASSED SINCE THE GULF WAR REFLECT SIGNIFICANT PROGRESS IN MINE WARFARE AND THE INDIVIDUAL WHO IS MOST RESPONSIBLE FOR WHAT I AM ABOUT TO TELL YOU IS THE SAME PERSON WHO INTRODUCED ME, ...RADM JOHN PEARSON..... FORTUNATELY FOR ME, THOSE PIECES OF PAPER IN THE NAVY CALLED ORDERS TOOK EFFECT LAST MONTH SO I AM THE LUCKY ONE WHO GETS TO ADDRESS YOU ON THIS SUBJECT TODAY.

OUR SPEAKERS AT EARLIER SESSIONS TODAY HAVE SUPERBLY ARTICULATED THE MINE THREAT AND ITS POTENTIAL IMPACT ON JOINT OPERATIONS. LET ME JUST REITERATE THAT UNLESS NAVAL EXPEDITIONARY FORCES PROJECT POWER AT THE TIME AND PLACE OF OUR

CHOOSING, AND THEN SUSTAIN THE BUILD-UP OF COMBAT FORCES ASHORE, WE WILL BE IRRELEVANT.

DESPITE THE INHERENT DIFFICULTIES OF THIS PARTICULAR ASPECT OF NAVAL WARFARE, I BELIEVE THAT THE GLASS IS HALF FULL AND THAT WE HAVE A "GOOD NEWS" STORY IN THE MAKING

CERTAINLY ONE OF THE HIGHLIGHTS OF THE PAST FIVE YEARS IS THE ESTABLISHMENT OF THE MINE WARFARE CENTER OF EXCELLENCE IN SOUTH TEXAS. IT IS UP AND RUNNING WITH SHIPS, AIRCRAFT, EOD, STAFFS, AND DEDICATED INFRASTRUCTURE ..... ALL CO-LOCATED FOR MAXIMUM SYNERGY AND SUPPORT. EVEN THOUGH WE ARE NOT YET AT 100 PERCENT WE ARE REAPING THE DIVIDENDS OF THIS VENTURE.

WITH REGARD TO OUR SURFACE MCM FORCE, WE ARE JUST 5 MINEHUNTERS (MHCS) SHORT OF OUR FULL FORCE. WE HAVE 14 MCM AVENGER CLASS HUNTERS/SWEEPERS

AND WEDNESDAY USS KINGFISHER , THE SEVENTH OSPREY CLASS MHC WILL ARRIVE IN INGLESIDE FOR THE FIRST TIME. THE LAST MHC WILL COMMISSION IN MAR 99 ..... USS INCHON, OUR MINE COUNTERMEASURES COMMAND AND SUPPORT SHIP COMPLETED CONVERSION EARLIER THIS SUMMER AND IS PROCEEDING NICELY THROUGH THE PACES OF HER WORKUP TO DEPLOY NEXT SPRING. WE HAVE ALREADY SEEN THE WARFIGHTING ENHANCEMENT FROM HER C4I SUITE IN JOINT TASK FORCE EXERCISE 97-1 WHICH I WILL DISCUSS FURTHER IN A FEW MOMENTS. HELICOPTER MINE SQUADRON FIFTEEN HAS ALSO ARRIVED AT NAS CORPUS CHRISTI AND, LIKE INCHON, IS MAKING REMARKABLE PROGRESS IN REGAINING READINESS FOLLOWING RELOCATION FROM ALAMEDA. I ANTICIPATE THAT HM-15 AIRCRAFT WILL OPERATE FROM INCHON FOR THE FIRST TIME NEXT MONTH.....SO YOU CAN SEE THAT IT IS ALL COMING TOGETHER AND WE NOW HAVE THE

OPPORTUNITY TO CONDUCT TRUE INTEGRATED TRAINING IN MCM, BOTH WITHIN OUR MCM FORCES, AND WITH THE FLEET AS WELL... THE FOREGOING CONSTITUTES A MAJOR PARADIGM SHIFT, AND IS CONSISTENT WITH CNO DIRECTION THAT WE FULLY INTEGRATE MINE WARFARE INTO FLEET TRAINING, EXERCISES, AND DEPLOYMENTS TO ELEVATE MINE WARFARE PLANNERS AS " EQUAL PARTNERS" ON OPERATIONAL STAFFS, IN ORDER TO ENSURE THAT MINE WARFARE CONSIDERATIONS ARE GIVEN THE HIGH VISIBILITY AND ATTENTION THEY REQUIRE. WHEREAS THE NAVAL COMMANDER USED TO DIAL "911 INGLESIDE" AND REQUEST ASSISTANCE TO ENABLE THE EXECUTION OF HIS PLAN WHICH HAD BEEN DEVELOPED IN MOST CASES WITHOUT IN-DEPTH CONSIDERATION OF THE MINE THREAT , WE ARE UNDERGOING THE "SEA CHANGE" WHEREIN THE IMPLICATIONS OF THE MINE THREAT WILL BE A PART OF THE OPERATIONAL PLANNING FROM THE BEGINNING, AND THE

PLAN WILL EVOLVE CONSISTENT WITH THE ACCOMMODATION AND RESOLUTION OF THE MINE PROBLEM. AS I MENTIONED EARLIER, WE TOOK A LARGE STEP FORWARD IN JOINT TASK FORCE EXERCISE 97-1 WHICH UNFOLDED ABOUT THE SAME TIME THAT JOHN PEARSON AND I WERE EXCHANGING SALUTES AT OUR CHANGE OF COMMAND. JTFEX 97-1 WAS THE GRADUATION EXERCISE FOR THE TR BATTLE GROUP AND THE NASSAU ARG PRIOR TO DEPLOYMENT. COMSECONDFLT WAS THE COMMANDER OF THE JTF. COMCMRON 2 WAS THE MCM COMMANDER EMBARKED IN INCHON WITH SURFACE MCM, EOD AND AIR MCM FORCES OPERATING IN THE GULF OF MEXICO. GEO TRANSLATION OF THE TACTICAL SITUATION IN THE GOM THROUGH OTCIXS/JIMCIS PROVIDED THE NAVAL COMMANDERS AND THEIR STAFFS IN THEIR FLAGSHIPS WITH DISPLAYS OF MIRROR -IMAGE MINEFIELDS OFF THE COAST OF NORTH CAROLINA ..... THE SAME PICTURE OF THE MINE PROBLEM

THAT COMCMRON 2 HAD ABOARD INCHON IN SOUTH TEXAS. LIAISON OFFICERS WITH MCM TACTICAL PLANNING EXPERTISE WERE PROVIDED EACH STAFF TO INJECT THE MAXIMUM DEGREE OF REALISM AND MCM TACTICAL THINKING INTO THESE STAFFS.

..... AND I AM PLEASED TO TELL YOU THAT THE MCM COMMANDER PLAYED A VITAL PART IN THE BG/ARG PLANNING OF OPERATIONS THROUGHOUT THE EXERCISE.

WHILE THE USE OF THE ELECTRONIC GEO-TRANSLATION TECHNIQUE DATES BACK TO EXERCISE KERNEL BLITZ IN 1995, THIS INTEGRATED PLAY INVOLVING THE CJTF AND BATTLE GROUPS WAS A NEW STEP AND WAS APPLAUDED BY BOTH C2F AND THE COMTRBATGRU.

AS WE CONDUCT THIS SYMPOSIUM, 157 OR 45 PCT OF OUR 351 SHIP NAVY IS UNDERWAY WITH 97 (28 PCT) SHIPS

FORWARD DEPLOYED., CONDUCTING EXERCISES AND OPERATIONS WITH 7 FOREIGN COUNTRIES. THOSE FORWARD DEPLOYED FORCES INCLUDE USS GUARDIAN AND PATRIOT IN THE SEVENTH FLEET AND USS ARDENT AND DEXTROUS IN THE FIFTH FLEET. HAVING THESE SHIPS FORWARD HAS NUMEROUS ADVANTAGES. NOT ONLY ARE THEY POSITIONED FOR A MORE TIMELY RESPONSE TO CRISIS, BUT THEY ARE WORKING ON A ROUTINE BASIS WITH OUR JAPANESE, KOREAN, AND GULF STATE ALLIES TO HONE THEIR SKILLS AND BECOME MORE INTEROPERABLE. LAST YEAR THESE SHIPS CONDUCTED OVER A HALF DOZEN EXERCISES IN EACH THEATER AND THIS YEAR THE NUMBER OF EXERCISE ARE PLANNED TO DOUBLE IN EACH THEATER. ADDITIONALLY, THEIR DEPLOYMENT IS CONSISTENT WITH OUR MIW CONCEPT OF OPERATIONS WHICH EMPHASIZES THE VALUE AND NEED FOR ENVIRONMENTAL AWARENESS, MAPPING, SURVEY, AND INTELLIGENCE OPERATIONS ON A

CONTINUING BASIS., NOT JUST WHEN WE ARE PREPARING FOR OPERATIONAL CONTINGENCIES.

WE DO NOT HAVE FORCES FORWARD DEPLOYED TO THE EUROPEAN THEATER, HOWEVER WE ARE ENGAGED WITH OUR ALLIES THERE AS WELL. SINCE '93 OUR FORCES HAVE PARTICIPATED IN THE BLUE HARRIER EXERCISE SERIES ON A BIANNUAL BASIS AND THIS COMING YEAR WE WILL PROVIDE THE MOST ROBUST FORCE EVER WITH INCHON, HM-14, EOD , 3 MCMS, AND FOR THE FIRST TIME AN MHC. BLUE HARRIER WILL TAKE PLACE NEAR DENMARK AND WILL BE FOLLOWED BY TWO MORE EXERCISES IN THE MED WITH SPAIN AND ITALY RESPECTIVELY. COMSIXTHFLT HAS REQUESTED AMCM PLAY WHICH FALLS OUTSIDE THE DEPLOYMENT SCHEDULE GUIDELINES FOR INCHON. THEREFORE, WE ARE CONSIDERING SHORE BASING AMCM ALONG WITH AN INNOVATIVE CONCEPT FOR STAGING AMCM EQUIPMENT IN

THEATER, AND THEN FORWARD DEPLOYING ADDITIONAL AIRCREWS TO MARRY UP WITH MH-53 AIRFRAMES BASED AT SIGONELLA AND THE PREPOSITIONED EQUIPMENT.

----- THIS IS FURTHER EVIDENCE OF OPERATIONAL FLEXIBILITY.

WITH SUCH IMPORTANCE PLACED ON HAVING OUR MCM FORCES FORWARD, IT IS CLEAR THAT OUR FLEET CINCS AND NUMBERED FLEET COMMANDERS SEE MINE WARFARE AS A VERY IMPORTANT INGREDIENT TO OVERALL NAVAL PRESENCE. MINE WARFARE FORCES HAVE BEEN INCLUDED IN FLEXIBLE DETERRENT OPTION PACKAGES THAT SUPPORT CRISIS RESPONSE PLANNING. THEY ARE CONSIDERED AN INTEGRAL PART IN THE EXECUTION AND SUCCESSFUL OUTCOME OF VARIOUS FLEET OPLANS. TIMELINES ARE CLEARLY CRITICAL TO THE SUCCESSFUL EXECUTION OF OPERATIONAL PLANS AND THE QUICK RESPONSE

CAPABILITY OF OUR AMCM AND EOD FORCES COMBINED WITH THE CONTINUED FORWARD PRESENCE OF SMCM UNITS GIVES US AN INITIAL JUMP ON THESE TIMELINES.

..... WHAT I HAVE JUST DESCRIBED TO YOU IS WHAT I THINK IS THE BEST MCM FORCE THAT OUR NAVY HAS EVER HAD. IT IS A MODERN FORCE WITH DEDICATED AND WELL MOTIVATED SAILORS. HAVING SAID THAT , IT ONLY PARTIALLY FULFILLS THE NAVY'S VISION OF WHAT IT NEEDS TO SUPPORT ITS PLAN FOR PACING THE THREAT, AND CONTINUING TO CLOSE THE GAP IN REQUIRED MCM CAPABILITY INTO THE 21ST CENTURY. .....WHEREAS DURING THE COLD WAR WE WERE CONCERNED WITH A BLUE WATER THREAT, Q-ROUTES, AND PORT BREAKOUT WITH SUFFICIENT REACTION TIME, ...OUR MISSION FOR TOMORROW IN THE LITTORALS IS ENVISIONED TO BE QUITE DIFFERENT. REACTION TIME WILL BE CRITICAL AND IN

ORDER TO CONDUCT EXPEDITIONARY OPERATIONS WE WILL HAVE TO DEAL WITH MINES IN THE SLOCS, SHALLOW WATER, VERY SHALLOW WATER, AND SURF AND CRAFT LANDING ZONES. SO I BELIEVE THAT YOU CAN SEE THAT THE DEDICATED FORCE OF TODAY, THE MAJORITY OF WHICH IS BASED IN SOUTH TEXAS NEEDS TO BE COMPLEMENTED BY NEW CAPABILITY WHICH IS FORWARD DEPLOYED IN OUR NAVAL FORCES. WE REFER TO IT AS "ORGANIC CAPABILITY" AND I WOULD LIKE TO EXPLAIN SOME OF THE INITIATIVES IN ORGANIC MINE COUNTERMEASURES WHICH ARE ALREADY UNDERWAY.

FIRST, LET ME BRIEFLY REVIEW OUR MINE WARFARE CONCEPT OF OPS AS IT IS THE BEDROCK FOR OUR REQUIREMENTS. THE GOAL OF OUR CONCEPT OF OPERATIONS IS TO : (1) PREVENT MINES FROM GOING IN THE WATER IN THE FIRST PLACE - - - - - THAT FAILING (2) TO ENABLE UNENCUMBERED MANEUVER OF NAVAL FORCES

AROUND MINED AREAS IF POSSIBLE, (3) EXPLOIT GAPS/WEAKNESSES IN DEFENSES, AND (4) FINALLY CLEAR MINES WHEN NECESSARY. THERE ARE FOUR BASIC SYNERGISTIC STEPS TO THE CONCEPT THAT BUILD ON AND OVERLAP WITH EACH OTHER TO PROVIDE NAVAL FORCES THE CAPABILITY TO COUNTER THE MINE THREAT. THE FIRST STEP IS MAPPING, SURVEY AND INTELLIGENCE OPERATIONS. ALTHOUGH WE CANNOT PINPOINT THE EXACT GEOGRAPHIC LOCATION WHERE OUR NAVAL FORCES WILL ENCOUNTER MINES, IT IS LIKELY THAT MINES WILL THREATEN THE LITTORAL REGION AND OTHER STRATEGIC CHOKEPOINTS. BOTTOM MAPPING AND ENVIRONMENTAL DATABASES HELP DETERMINE THE EXTENT OF MINEABLE WATERS AND THE BEST ROUTES FOR MINEHUNTING. THE SECOND STEP IS TO INITIATE THE SURVEILLANCE OF POTENTIAL MINELAYERS, ESPECIALLY IN TACTICALLY IMPORTANT AREAS DURING TIMES OF RISING TENSION. THE THIRD STEP AND THE ONE

WHICH WILL BE A REAL FORCE MULTIPLIER IF WE CAN ACHIEVE THE CAPABILITY IS THE USE OF ORGANIC MINE COUNTERMEASURES, WHICH WOULD RESIDE IN ALL OF OUR FORWARD DEPLOYED BATTLEGROUPS. THESE ORGANIC SYSTEMS ARE ENVISIONED TO PROVIDE US THE CAPABILITY TO PROVIDE, AS A MINIMUM, LOW OBSERVABLE RECONNAISSANCE AND NEUTRALIZATION CAPABILITY SUFFICIENT TO ENABLE POWER PROJECTION WITH ACCEPTABLE RISK TO OUR FORCES. THE FOURTH AND FINAL STEP IS THE CLEARANCE BY OUR DEDICATED FORCES OF THOSE MINES IMPEDING SUSTAINED POWER PROJECTION .

LAST FALL ADMIRAL BOORDA DIRECTED THE MINEWARFARE COMMUNITY, WHOSE THREE PRINCIPLE MEMBERS ARE THE DIRECTOR OF EXPEDITIONARY WARFARE (N85), COMINEWARCOM, AND PROGRAM EXECUTIVE OFFICER (MIW), TO PERFORM A COMPLETE SCRUB OF THE MINE

WARFARE PROGRAM TO REVALIDATE SHORTFALLS IN CAPABILITY AND TO ENSURE THAT NO REDUNDANCY EXISTED. HE WANTED US TO HAVE CONFIDENCE THAT WE WERE GETTING THE MAXIMUM BANG FOR THE BUCK. HE ALSO CHALLENGED US TO PUT NEW CAPABILITY INTO THE HANDS OF OUR SAILORS AT THE EARLIEST OPPORTUNITY.

..... OUT OF THAT DIRECTION CAME THE DEVELOPMENT OF THE CONCEPT OF OPERATIONS WHICH I JUST DISCUSSED AND A MIW PLAN WHICH FOCUSES ON CAPABILITY REQUIRED IN THE NEAR TERM, MID-TERM, AND LONG TERM. THE NEAR TERM IS DEFINED AS THE CURRENT YEAR OF EXECUTION AND THE FOLLOWING YEAR.--- - THE MID TERM IS THE POM YEARS, BEGINNING IN '98 AND THE FAR TERM THE YEAR 2003 AND BEYOND. THE FY 96-97 MIW PLAN CONTAINED SEVERAL INITIATIVES FOR PROTOTYPE ORGANIC

MCM SYSTEMS OPERATING FROM SURFACE SHIPS AND SUBMARINES.

THE FIRST, THE REMOTE MINEHUNTING SYSTEM (ORIGINALLY CALLED RMOP) IS A SEMI-SUBMERSIBLE DOLPHIN VEHICLE WHICH TOWS THE AQS-14 SONAR. IT IS AUTONOMOUS AND HAS APPROXIMATELY 24 HRS ENDURANCE OPERATING ON A DIESEL ENGINE. VEHICLE CONTROL AND DATA EXCHANGE ARE CURRENTLY LIMITED TO RF RANGE, HOWEVER OTH CAPABILITY IS A REQUIREMENT FOR THE MATURE SYSTEM WHICH IS A MID TERM PROGRAM AND DUE IN THE FLEET AT THE TURN OF THE CENTURY. THE SYSTEM WAS FIRST TESTED IN EXERCISE KERNEL BLITZ 95 AND WE ARE ABOUT TO TAKE A STEP FORWARD BY EMBARKING IT IN USS CUSHING (DD985) IN THE KITTYHAWK BG, AND OPERATING IT IN THE PERSIAN GULF. (*CUSHING'S BOAT DAVIT..... HAS BEEN MOD.....) IT WILL BE

EMPLOYED IN A 5TH FLEET EXERCISE IN JANUARY ALONG WITH DEXTROUS AND ARDENT UNDER THE COMMAND OF COMCMRON2. I WOULD ADD A FOOTNOTE HERE THAT THIS EXERCISE WILL ALSO INCLUDE ANOTHER ELEMENT OF THE NEAR TERM PLAN WHICH IS THE MIREM, OR MINE READINESS AND EFFECTIVENESS MEASUREMENT PROGRAM . MIREM WILL PERFORM DETAILED ANALYSES OF MIW BASELINE CAPABILITIES FOR VALIDATION SIMILAR TO THAT PERFORMED FOR ASW UNDER SHAREM. A DETAILED BRIEF OF MIREM IS BEING CONDUCTED LATER ON IN THE SYMPOSIUM. A SECOND SYSTEM IN THE MID-TERM PLAN IS THE NMRS UUV TO OPERATE FROM SSNS. THIS VEHICLE WILL BE TETHERED AND WILL TAKE US A BIG STEP IN THE DIRECTION OF THE AUTONOMOUS LMRS FOR THE FAR TERM.

FINALLY, PROTOTYPE ORGANIC CAPABILITY FOR NEAR TERM EMPLOYMENT FROM HELICOPTERS IS THE LASER MINE

DETECTION SYSTEM ONBOARD THE SH2G HELICOPTER, THE SYSTEM CURRENTLY KNOWN AS MAGIC LANTERN. THE FIRST OF THREE SYSTEMS WILL BE ROLLED OUT IN AN SH2G IN WILLOW GROVE NEXT MONTH AND WE ARE LOOKING FORWARD TO ITS FIRST EMPLOYMENT FROM A SURFACE COMBATANT IN THE NOT TOO DISTANT FUTURE. WE HOPE THIS SYSTEM WILL BE THE FORERUNNER OF A MATURE MID TERM SYSTEM UNDER THE ADVANCED LASER MINE DETECTION SYSTEM PROGRAM FOR OPERATION FROM THE SH60 HELICOPTER. I WOULD POINT OUT THAT IT IS OUR INTENTION FOR ALL THESE SYSTEMS, BOTH SHIP AND AIR, TO BE "PLUG-IN" TYPE WITH THE HOST PLATFORM HAVING INTEGRATED COMBAT SYSTEMS CAPABLE OF RECEIVING THE DATA, DISPLAYING IT AS REQUIRED, AND PASSING IT TO THE COMMANDER REQUIRING THE DATA.

AS I NOTED EARLIER, WE NEED TO FOCUS ON THE VERY SHALLOW WATER AND CRAFT LANDING ZONE AS WE SHIFT TO THE LITTORALS.

THE NEAR AND MID TERM PLANS ADDRESS THIS SHORTFALL IN CAPABILITY. A VERY SHALLOW WATER MCM DETACHMENT HAS BEEN FORMED IN CORONADO TO DEVELOP TACTICS AND EXPLORE TECHNOLOGY FOR LOCATING AND NEUTRALIZING MINES AND OBSTACLES IN THIS VITAL ZONE. THE DETACHMENT IS COMPRISED OF NAVY SEALS, MARINE FORCE RECON, AND EOD PERSONNEL. MARINE MAMMALS ARE ALSO BEING UTILIZED. ADDITIONALLY, WE ARE PURSUING DISTRIBUTIVE EXPLOSIVE TECHNOLOGY TO ENABLE BREACHING IN THESE VERY SHALLOW WATERS AND IN THE SURF AND CRAFT LANDING ZONES.

THIS IS A GOOD BEGINNING IN A VERY DIFFICULT AREA.

EARLIER I MENTIONED THAT THE MINE WARFARE COMMUNITY HAS BANDED TOGETHER TO MEET THE CHALLENGE. WHILE THE THREE PRINCIPALS (THAT IS N-85, CMWC AND PEO (MIW)) REMAIN AT THE CORE OF THE COMMUNITY, EVERY ATTEMPT IS BEING MADE TO INCLUDE OUR LABS, INDUSTRY, AND ACADEMIA IN OUR PURSUIT OF EXCELLENCE IN MINE WARFARE. THERE IS NO QUESTION THAT IN THE MID AND FAR TERM, WE WILL NEED SOLUTIONS FROM SCIENCE AND TECHNOLOGY TO PROVIDE US WITH ADVANCED SENSORS FOR USE IN UNMANNED UNDERWATER VEHICLES, UNMANNED AIR VEHICLES, AND FOR MINE NEUTRALIZATION FROM ORGANIC PLATFORMS. OUR GOAL IN THE FAR TERM WILL BE TO ACHIEVE THE CAPABILITIES FOR REAL-TIME, RAPID MINE RECONAISSANCE, AND RAPID MINE

CLEARANCE, TO IN-FACT REDUCE THE IMPACT OF MINES TO THAT OF A SPEED BUMP.

AND SO, WHILE MANY CHALLENGES REMAIN, I AM ENCOURAGED BY OUR CONTINUING PROGRESS. MINE WARFARE IS "EVERYBODY'S PROBLEM" AND IT IS NOW CLEARLY IN OUR MAINSTREAM.

I APPRECIATE YOUR SUPPORT AS REFLECTED BY YOUR PARTICIPATION AND I ANTICIPATE GREAT STRIDES FORWARD AS A RESULT OF THIS SYMPOSIUM.

The Future of the Pacific Fleet

RADM John F. Sigler, USN
Deputy and Chief of Staff,
Commander-in-Chief, U.S. Pacific Fleet

I'm happy to be back in Monterey - it's a good transition from the 40 degree weather in Washington before my return to the balmy 80s of Hawaii. I'm here today as the Deputy Commander in Chief of the U. S. Pacific Fleet, but I want you to know that I am also here because I have a deep appreciation for mine warfare.

Let me give you a little background on my exposure to mine warfare: I started out as a junior captain as Director for Plans and Policy on C7F staff. I saw that mines were a show stopper for both a Soviet Union and Korean contingency. After my major command in BELKNAP, I went back to the Plans & Policy arena at CINCLANTFLT. I was involved with the standup of COMMINEWARCOM as advocate, sponsor and TYCOM for mine warfare and their subsequent move to Ingleside.
Next I served as COMPHIBGRU ONE which meant going back to plans for Korea. During that time I was involved with the forward deployment of PATRIOT & GUARDIAN and the rotation of their

crews. When I reported to CINCPACFLT I initially was the DCOS for Operations, Plans and Communications. Later I put on an additional hat as the DCOS for Resources. I saw first hand the underfunding/atrophy of offensive mine capabilities and learned that it's critical that mine warfare not separate itself from the fleets AND that the fleets not underplay MIW during tight budget times. I think that one of the problems we're having in mine warfare today is that we're looking East to the Atlantic environment. I think that the real potential for mine warfare to impact our lives is in the Pacific region. Therefore, today, I want to talk about that environment in the Pacific. followed by a discussion on where we're going.

Since Goldwater - Nichols, the mission of the Pacific Fleet Commander in Chief has changed from warfighter to force provider. Our mission is two-fold 1) to support USCINCPACs Theater strategy and 2) to provide Unified Commanders with interoperable, combat-ready Naval forces. You'll notice the word 'interoperable' that is a linchpin of today's joint and combined operations and key to CINCPACFLT's mission.

The Pacific Fleet's area of responsibility is the largest of the three, extending from our West Coast across the date line and 17 time zones to the East Coast of Africa. We use the term area of

responsibility because our area of operations is global with electronic warfare aircraft and Pacific Seabees in Europe, Pacific ships often in the Atlantic for counter-drug operations and our TACAMO aircraft spread around the world.

The size of our area of responsibility is one of the determinants of how we operate because it just plain takes a long time to get anywhere in the Pacific and Indian Oceans.

Perhaps the most notable feature of our area, besides it's size and population is it's emergence as the world's economic powerhouse. There are currently nine economies in the world with annual growth rates of over 6% -- eight of them are in Asia, and China, for example, is currently seeing GDP growth of 12 - 14% a year.

The GDP of the region caught up with and exceeded that of Europe in the early part of this decade, and the gap is predicted to grow well into the next century.

The impact of this growth on the United States is significant. Our trade with Asian nations exceeds that of any other region and the percentage, like the Asian GDP's, is growing. No one should be surprised that the vast majority of that trade takes place by ocean transport. This makes it very vulnerable to mine warfare.

Our friends in the Pacific are extremely dependent on Sea Lines of Communication and their and their dependence on Mideast oil is almost absolute. Maintaining the freedom of these sea trade routes is absolutely essential to continued economic growth in the region. Closure in wartime could be equally devastating.

United States interests in the region are both clear and vital. There are 3 million U.S. jobs directly tied to trade in the region, and if you include the trickle down effect 9 million jobs are dependent on that trade. By the end of the next decade those numbers are expected to grow to 6 million and 18 million U.S. jobs respectively. American pocketbooks are inextricably linked to the economies of the Asia-Pacific rim. Clearly stability in the region is critical, not only to continued Asian prosperity, but to the well-being of the United States.

The problem, of course, is that stability is not guaranteed. In fact historic animosities abound in the region, and although we thankfully have peace throughout the Pacific, it is an uneasy peace that our forward deployed forces seek to maintain on a daily basis,

and that unfortunately, is particularly fragile in a couple of areas like the Korean Peninsula.

So our concerns are that the pressures of continued growth in the region when combined with historic animosities, set a continuing stage for regional instability, with potentially dire results for the peoples of the Pacific and the U.S. economy. Further that instability itself can reach U.S. shores through terrorism, proliferation of weapons of mass destruction, or a continued growth in Pacific drug trafficking and illegal alien smuggling.

Wherever any of us travel in the region, a common theme among those we talk to is the much appreciated role that the Pacific Fleet plays as part of the forward deployed force, by sustained forward presence, in regional security and stability. There is however another common and growing theme, and that is a perception of U.S. lack of concern and withdrawal from Asia.

At the end of WWII the Pacific Fleet consisted of almost 5000 ships. By Vietnam we had about a tenth of that total, and by the close of the Cold War we were down to under 300 ships. Today your Pacific Fleet is at 194 ships. On the other hand our

ships today are much larger and far more lethal than their World War II counterparts. Of course, the cost has risen by orders of magnitude as well. An interesting point in all of this is that, with the exception of battleships, the types of ships that we have today are essentially the same as they were over 50 years ago.

I think that is a trend that will continue for the foreseeable future. Although this is arguable, it is my sense that our ships, aircraft and weapons systems that will carry us well into the next century will evolve from current designs and concepts. Even the arsenal ship is not, in my opinion, a radical departure in it's hull, propulsion, survivability or robust loadout. What is very different about arsenal is it's command and control possibilities. And that is where the revolution in Naval warfare is and will continue to take place -- in C4I. With cooperative engagement coming on line the potential for arsenal is enormous. Information warfare, much in the news lately, will be an increasingly important facet of how we fight and what we need to defend. Through an extraordinary expansion in actual and virtual bandwidth we're facing a future - not far off - when the very foundations of naval warfare command and control may see radical change, and where our knowledge of the battlefield will approach ground truth. In command and

control, for example, we may be able to discard the hierarchical arrangement with us since the Peloponnesian Wars for a networked nodal disposition with extraordinary agility, redundancy and survivability.

Our concept for the near to mid-term in the Pacific Fleet is centered around the desktop, fully compatible PC, that will provide the warfighter with all of the connectivity, processed and fused information, and planning and execution tools required for both operations and administration in one spot.

But where are we now? The news is not good. Under the current way of doing business we are well short of the experts required to implement a robust AIS needed to move ahead, which explains - partly - why only 40% of our commands have local area network and only 10% have access to the worldwide web. Looming ahead as we move toward full DMS implementation by '99 the Fleet is facing a potential $330 million bill to bring Fleet PC's into compliance, as well as an undetermined solution to the challenge of multi-level security.

We're facing a real challenge finding solutions with likely budgets that don't match validated requirements - an estimated $2 billion shortfall across the FYDP. One of the keys - if there is to

be a solution - is continuing to find new ways to do business, to stretch current resources and to improve planning to optimize performance per dollar.

Our plan is to neck down the current plethora of systems, to install adequate multi-level security and to present everything to the user in one place.

The solution, in our opinion, must come from commercial off the shelf systems and software - COTS. We've entered an era where we can no longer afford unique systems where we bear the costs of not only development, but upgrades and specialized maintenance and training as well. And many of the companies which are the most innovative are not interested in stove piped systems and defense contracting, because their real profits come from quick reaction to market needs and a huge commercial customer base. And finally, COT's provides a level of interoperability that is especially attractive in working with other U.S. and foreign armed forces.

COTs then becomes the bridge that takes us from a proliferation of unaffordable stove piped systems to our goal of the single PC presentation to our users. Clearly if the Fleet is going to this, the Mine Warfare Community needs to follow suit.

Moving to single PC presentation as well as ensuring DMS compliance as economically as possible has led us to centralizing our AIS efforts into what we call Regional Information Technology Centers, or RITC's. The key is to balance responsiveness to customer needs with the economies of scale available from centralizing efforts. Interestingly, regionalizing AIS fits perfectly into our recently established shore station management and regional maintenance organizations, and will allow us to achieve the standardization required by the Information Technology 21 architecture, Defense Information Infrastructure, Defense Messaging System and Base Level Information Infrastructure.

In the RITC construct CINCPACFLT will establish policy and oversee fleet-wide implementation, including standardization. The regional centers will come under the area commanders of our four fleet concentrations in Hawaii, San Diego, the Pacific Northwest and the Western Pacific, and will be responsive to the unique needs of each. Each RITC will have systems administrators, centralized multi-level security, systems engineers for installation and upgrades, contracting and acquisition authority to achieve economies of scale and most importantly, responsive

support to the numerous commands, including our ships, in each region. Our initial estimates are that RITC will correct fully our infrastructure shortfalls, while saving at least 100 current billets and several million dollars per year in current costs. Thereby providing more with less.

A third tenet of Pacific Fleet C4I operations is the installation and integration of fully joint C4I suites in our fleet, battle group and amphibious ready group flagships. Our nuclear and conventional carriers and big deck amphibious ships are equipped to support naval commanders, including JFACC afloat, in joint operations. And our two fleet command ships, BLUERIDGE and CORONADO, are being made capable of supporting multi-service joint task force commanders and staffs. Both ships are being designed to accommodate both hardware and systems architecture changes in the future with a minimum of disruption. It is important that INCHON have compatible C4I systems.

And again, the vision is to move towards availability of operational and administrative information and connectivity in one location, the desktop PC. A fourth tenet of our C4I falls into the category of "campaign planning tools."

Most of you should be familiar with the decision and execution loops in both peace and war. In peace, we start by drafting war plans, then we evaluate courses of action, assess their impact, develop new courses of action, select the best and then begin the iterative cycle again. In war, we execute courses of action, assess the measures of effectiveness, apply lessons learned, develop new courses of action, select the best one and begin again. What we want to do is provide the warfighter with a single tool that can assist in both deliberate and crisis planning, quickly evaluate the plans using appropriate measures of effectiveness, and revise the plan to increase its effectiveness. The system is the Naval Simulation System, or NSS.

CINCPACFLT is a lead site for development of NSS, which is being designed not only to meet the primary goal of operational planning and execution, but will support as well both wargaming and the systems assessment process for POM decisions. NSS will form the Navy component of a joint modeling and simulation architecture. Mine warfare planning and execution is to be an integral part of NSS.

To summarize, Pacific Fleet C4I initiatives including the four keystones that I've just described:

- High performance PC based computing
- Regionalization of our AIS requirements
- Robust command ships, and
- The Naval Simulation System.

All of the C4I initiatives that I've just described are ongoing and have been or will be brought on-line in the relatively near-term. The final question that we are working on is: where do we go in the future - 10, 15 or more years out? There are a discrete number of parameters that determine what our fleet will look like in the future. They are: Mission, Budget, Threat, Technology, Synergy and Forward Basing. The last one, forward basing, is somewhat unique to the Pacific because of the vast distances over which we operate. To achieve the same level of forward presence and contingency response provided by our 18 ships forward based in Japan, including PATRIOT & GUARDIAN would require 36 to 54 additional ships homeported on the West Coast or in Hawaii. And, of course, forward basing, both in terms of our national will and host nation support, is not guaranteed in the future.

A challenge we face as we map our future is the seemingly incompatible life cycles of our hardware. A ship built today could still be with us in 2040! MIDWAY for example, served us ably

for 46 years until her retirement just 4 years ago. Likewise, a particular type of aircraft may be with us for a long time -- P-3's first appeared in 1961, and A-6's in 1963. Even the relatively "new" F-14 has served for over 24 years. At the same time, we are seeing an acceleration in C4I hardware that now presents us with a new generation on the average every 18 months.

So how do we move ahead? Currently at Pacific Fleet headquarters we are preparing, with the Center for Naval Analysis, our answer to that question using a strategic planning tool developed by Peter Schwartz for the Dutch Shell Oil Corporation, which he calls "Scenario Based Planning." The two premises of the model are that we cannot with certainty predict the future and that circumstances seemingly unrelated to our mission may, in fact, have a profound affect upon us. For example, a regional shortage of fresh water could lead to internal or external crisis that would involve naval forces across the spectrum of humanitarian assistance to combat. Scenario based planning postulates 3 or 4 plausible scenarios within the planning horizon using multi-disciplinary analysts to "think out of the box," and then develops 3 or 4 corporate postures for the same time frame. The resulting matrix will be examined in detail to gain insight into our

possibilities, to allow formulation of a strategic vision that will get us from where we are to where we want to be. We have chosen a 15 year horizon because that represents the approximate half-life of a ship built today and is relatively manageable.

Our scenario has 5 givens:

1. Our geography won't change and even if we have much faster ships it will still take a long time to get anywhere in our areas of operations. Further, the region will continue to have critical focal points, like the Straits of Malacca, that can directly affect the United States' well being. Those two points are especially critical in our mine countermeasures capabilities.

2. We will have an increasingly globally interlocked economy which will keep U.S. interests global, and the Asia Pacific influence in that global economy will remain preeminent.

3. Friction, conflict and crisis -- including natural and environmental crisis and terrorism -- will continue to threaten regional stability and U.S. interests.

4. The great majority of trade in the Pacific and Indian Oceans will continue to be by sea-going vessels, implying a continued requirement for freedom of the seas, particularly in the sea lines of communication or SLOCs.

5. U.S. Naval Forces, operating alone or as part of larger joint or combined forces, will remain mobile, flexible and sustainable and will remain in demand as an instrument of U.S. national policy.

The trends we see in the future include increasing U.S. trade with the region and faster economic growth in the near term with a flattening in the long term for Asia. This implies an increasing regional competition for markets, for access to a limited money supply and for constrained natural resources.

- Technological change will continue to accelerate. As I mentioned we're down to 18 months for computing generations. And as military technology is increasingly driven by commercial developments we will see both the same acceleration and greater availability to anyone who can afford it. And more nations and organizations will be able to afford advanced technology as competition drives down prices and overheated economies provide more capital.

- At the same time, U.S. defense budgets may show slight growth, but flat or declining budgets are more likely as deficit reduction and other competing demands rise in perceived relative importance.

At the same time there are more than enough unknowns about our future in the Pacific to make our planning a real challenge.

- Will the outcome in Korea be a hard or soft landing and where will a post-unified Korea's interests be?

- What is China's intent that accompanies a rapidly improving military capability? What will happen in Hong Kong, Taiwan and the Spratleys?

Will China, under new leadership about to emerge, be able to sustain both a communist government and an overheated capitalist economy?

- How long will it take for a Russian economic recovery and what direction might they go?

- What about proliferation of weapons of mass destruction in the region, or the affect of transitional movements like a potential rise of fundamentalism in currently moderate Asian Muslim populations?

- And what will be our perceived and actual regional influence as our military gets smaller and our economic impact in the region is reduced as a percentage of the total. Will we have continued

access to forward basing? What would be the affect on regional stability of significantly reduced U.S. influence?

We started this strategic planning in January and are close to finalizing it as I speak. Three sets of scenarios for the primary areas of Pacific Fleet interests have been developed, focusing on Asia Pacific, Middle East and Latin America and range in each case from a kinder-gentler world to the bad news we would hope to deter.

And we are currently developing the baseline for potential fleet postures in the years beyond 2010 that will range from a robust, forward deployed, well equipped Navy to a smaller, in-garrison force brought home by a combination of dwindling dollars and national will.

As I have said, our final phase of the study will be to study the interaction of plausible scenarios with potential force postures. Our preliminary conclusions are listed here:

- First we need to stay forward deployed if the expense of naval forces is going to continue to be cost beneficial to our nation.

- Second, we need to recognize always that it is the men and women in the loop that make the difference between a great and an inadequate Navy. The foremost contributor to quality of life is

job satisfaction. If we continue to equip, train and support our people adequately they will continue to make us the best Navy in history.

- As we look to the future we clearly have to leverage technology to keep us ahead of our competition. Although we need to design continually whatever the next generations of ships and aircraft might be, we have what we have and keeping a 25 year old ship relevant is possible only if we've followed a strategy that allows flexible and increasingly rapid response to emergent developments. We should note that because of C4I, 35 year old carrier KITTY HAWK is as capable a warfighter as the 7 month old nuclear carrier STENNIS.

- And finally it is clear that technological developments - with us now and impending - are going to allow us to change the way we do business. We as a Fleet and as a Navy need to develop the corporate agility I mentioned earlier. Our belief is that winning in the future will consist of getting to and implementing the solution faster and with greater clarity that the other guy.

Back in Hawaii Admiral Clemins now occupies the same office and sits at the same desk that Fleet Admiral Nimitz used during WWII. The entry to his office has just been remodeled into

a small museum displaying Nimitz and Pacific Fleet memorabilia. All of you are invited to come. On one of the walls is a quote from Admiral Nimitz, it reads: "We must make certain, now and for the future, that peace is secure. We must remain strong. Never again should we risk the threat which weakness invites." This quote spoken in 1945 is more true today than ever and must form the basis of our future as a Navy. Thank you.

The Joint Mine Countermeasures/Countermine Advanced Concepts Technology Demonstration (ACTD) Process

Mr. Mike Jennings,
Joint Countermine ACTD Demo I Program Manager
and
Dr. Doug Todoroff,
Director of Mine Research,
Office of Naval Research

The objective of the Joint Countermine ACTD is to demonstrate the capability to conduct seamless amphibious mine countermeasure (MCM) operations from sea to land. The demonstration will be accomplished by integrating Army, Navy, and Marine Corps technology developments and fielded military equipment. This ACTD will demonstrate the coupling of selected current capabilities with developing capabilities, leading to enhanced integration of joint capabilities to conduct countermine operations. The ACTD will also seek to identify improvements in the capabilities being developed or envisioned. The ultimate goal is to demonstrate emerging MCM technologies, operational concepts, and doctrine in MCM support of amphibious and other operations involving Operational Maneuver From the Sea (OMFTS) and follow-on land operations.

The Joint Countermine ACTD consists of two closely connected demos. Demo I, planned for FY-97, focuses on the near-shore capabilities with emphasis on in-stride detection and neutralization of mines and obstacles in the beach zone and on land. The Army is lead service for this demo. Demo II, planned for FY-98, emphasizes the technologies of clandestine surveillance and reconnaissance as described in the Navy FY-94 Mine Warfare Plan and demonstrates all elements of a seamless transition of countermine operations from the sea to the land. The Navy is lead service for this demo.

The Joint Countermine ACTD will employ prototypes for Advanced Technology Demonstrations (ATD) and pre-production phases of the development cycle along with fielded equipment in live demonstrations. In addition, a robust modeling and simulation effort, JCOS, will expand the information base obtained from the live demos through constructive modeling and DIS. C4I connectivity and notional architectures for MCM will also be demonstrated. Extensive operational user involvement supports the development and evaluation of doctrine, tactics, techniques, and procedures and the assessment of organizational impacts of the new technology prototypes. Select items of equipment and simulations will remain with the operational user as residuals for a two-year extended evaluation.

The Executing Agents for the Joint Countermine ACTD are the Deputy for Research and Technology, Office of the Assistant Secretary of the Army for Research, Development, and Acquisition, **Dr. A. Fenner Milton** and the Chief of Naval Research, **RADM Paul G. Gaffney, II.** For more information contact Joint Countermine ACTD Demo I Program Manager, **Mr. Mike Jennings**, on 703-704-1032, e-mail: mjenning@nvl.army.mil, or Demo II Program Manager, **Col T.J. Singleton**, USMC, on 703-696-1299; e-mail: singlet@onr.navy.mil

Joint Countermine ACTD Novel Systems

Navy Systems

- **Advanced Sensors**
- **Magic Lantern (Adaptation) [ML(A)]**
- **Advanced Lightweight Influence Sweep System (ALISS) ATD**
- **Explosive Neutralization Advanced Technology Demonstration (ENATD)**
- **Near Term Mine Reconnaissance System (NMRS)**
- **Littoral Remote Sensing (LRS)**

Marine Corps Systems

- **Coastal Battlefield Reconnaissance and Analysis (COBRA)**
- **Joint Amphibious Mine Countermeasures (JAMC)**

Joint USMC/Army Systems

- **Off-Route Smart Mine Clearance (ORSMC)**

Army Systems

- **Close-In Man-portable Mine Detector (CIMMD)**
- **Airborne Standoff Minefield Detection System (ASTAMIDS)**
- **Army Classified Program (ACP)**

Joint Countermine Advanced Concept Technology Demonstration (ACTD)

Navy Systems

Advanced Sensors

System functions: Underwater mine detection, classification, and identification in support of finding minefield gaps.

Description: Advanced sensors will replace the AN/AQS-14 sonar in the RMS tow body. These sensors will expand the RMS capability. Search rates in deep water against moored mines will equal 6sq nmi hr. Sensor search rate in shallow water and very shallow water will decrease in accordance with the decrease in threat area. Sensor data fusion will provide D/C/I against all sea mines. System endurance will provide an 8-12 knot search speed for up to 24 hours on a single tank of fuel. For more information contact **Dr. W. Ching**, ONR 321, on 703-696-0804; e-mail: chingw@onr.navy.mil

Magic Lantern (Adaptation) (ML(A))

System function: To rapidly detect and classify minefields and obstacles in the very shallow water, surf zone, and craft landing zone.

Description: The ML(A) ACTD system will demonstrate the capability of gated, LIDAR imaging for detection of minefields and obstacles. The ACTD objective will be to demonstrate a capability to rapidly detect, classify and localize minefields and obstacles in the surf zone and craft landing zone. ML(A) will be operationally demonstrated during both Demo I and Demo II. The major components of ML(A) are the laser transmitter, scanner, cameras, bottom follower, GPS and processor. The system will also employ real-time automatic target recognition (ATR) and a datalink to ground station for viewing target images. For Demo II, the ML(A) ACTD System will demonstrate a further improved ATR algorithm and an enhanced tactical decision aid (TDA) for the surf zone mission. For more information contact **Dr. W. Ching**, ONR 321, 703-696-0804; e-mail: chingw@ onr.navy.mil

Advanced Lightweight Influence Sweep System (ALISS) ATD

The purpose of the Advanced Lightweight Influence Sweep System Advanced Technology Demonstration (ALISS ATD) is to demonstrate the ability to successfully conduct autonomous influence sweeping of magnetic and acoustic influence mines targeted against amphibious assault craft in very shallow waters. ALISS will utilize superconducting magnet and plasma-discharge pulse power technology to provide a high-speed lightweight acoustic and magnetic signature emulation sweeping capability. This technology will also significantly reduce sweep power requirements. ALISS may eventually be deployed from a variety of platforms (helicopter, ship, LCAC, or remote/autonomous controlled boat). During its demonstration in the Joint Countermine ACTD, it will be installed on a Rigid Hull Inflatable Boat for autonomous influence sweeping of the intended amphibious assault lanes. For more information contact **Mr. Steve Collignon**, ONR 32CM, on 703-696-3039; e-mail: colligs@onr.navy.mil

Joint Countermine Advanced Concept Technology Demonstration (ACTD) (Continued)

Joint Amphibious Mine Countermeasures (JAMC)

System function: The Joint Amphibious Mine Countermeasures (JAMC) system will provide the fleet marine forces the capability to clear mines and light obstacles from the high water mark to the craft landing zone in support of an amphibious assault, but not as the lead assault element.

Description: JAMC is a multi-functional landmine countermeasures system being developed for minefield/obstacle breaching and CLZ clearance during assault operations as well as rapid follow on clearance The system employs remote controlled tractors with mechanical, explosive and electro-magnetic MCM sub-systems in addition to visual and electronic marking devices. The multiple MCM and marking sub-systems allow very high clearance levels and positive marking for all ground elements of the assault force. JAMC development involves development of several new MCM subsystems and integration of existing MCM equipment. For more information contact MARCORSYSCOM/**LtCol W. Hamm**, on 703-640-2220.

Joint USMC/Army Systems

Off-Route Smart Mine Clearance (ORSMC)

System function: To neutralize off-route smart side attack and top attack mines.

Description: Consists of a tele-operated HMMWV platform that replicates critical signatures of target vehicles in order to cause a launch of the smart mine munition. The system is designed to avoid detection by the munitions sensors through the use of signature management techniques. Two systems are planned to be provided to the ACTD for both Demo I and II. Major components of the system include a tele-operated HMMWV, acoustic subsystem, seismic subsystem, signature management suite, and an IR decoy. The demonstration should include the use of the ORSMC developed smart mine simulator system in order to demonstrate the effectiveness of smart mine technologies against actual target vehicles and then to demonstrate the use of the ORSMC platform to neutralize these types of mines. For more information contact MARCORSYSCOM/**LtCol W. Hamm**, on 703-640-2220.

Army Systems

Close-In Man-portable Mine Detector (CIMMD)

System function: Detects surface and buried metallic and nonmetallic landmines.

Description: The CIMMD Program has developed a standoff IR Thermal Imager (IRTI), and a confirming Ground Penetrating Radar (GPR) brassboard man-portable mine detector. These detectors, which may be employed singularly or in combination are suitably packaged and available for inclusion in Warfighting Experiments. The standoff IRTI system has a backpack that includes an image processor and batteries; a helmet with an eyepiece display and COTS forward looking infrared. The IRTI system weight is approximately 30 pounds with batteries divided between the backpack (25 lbs) and helmet (5 lbs). The GPR system closely resembles the configuration of the U.S. Army AN/PSS-12 metal detector. The wand contains an electronics package, the antenna, and an LCD display. A backpack contains batteries. The GPR system weight is approximately 25 lbs with batteries -- divided between the backpack (10 lbs) and wand (15 lbs). For more information contact CECOM RDEC/**Mr. Mark Locke**, on 703-704-2418.

Joint Countermine Advanced Concept Technology Demonstration (ACTD) (Continued)

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Office of Naval Research Initiatives

Autonomous Oceanographic Sampling Network (AOSN)

Autonomous Oceanographic Sampling Networks (AOSN), when fully developed, will revolutionize ocean sampling by providing the individual investigator with affordable personal platforms and by fostering a new way of thinking in design and execution of in-situ experiments utilizing the power of spatial and temporal adaptive sampling and the diversity of network coverage. Sampling is done with several autonomous underwater vehicles (AUVs) as well as distributed acoustic and point sensors. The objective is to combine the best features of each method for increased mapping resoultion. AUVs traverse the network recording temperature, salinity, velocity, and other data, relaying key observations to the network nodes in real time and transferring more complete data sets after docking at a note. The technology will have a major impact in a number of applications including satellite remote sensing calibration, pollution and fisheries monitoring, mine hunting, salvage and open boundary data acquisition for weather and ocean forecast models. For more information contact **Dr. Tom Curtin**, ONR 322, on 703-696-4119; e-mail: curtint@onr.navy.mil

Rapid Airborne Mine Neutralization Advanced Technology Demonstration (RAMICS ATD)

The purpose of the Rapid Airborne Mine Neutralization System Advanced Technology Demonstration (RAMICS ATD) is to demonstrate the capability to rapidly identify, target, and destroy surface and subsurface mines in deep and shallow water with minimum risk to personnel and equipment. RAMICS will employ a LIDAR-based targeting system and hypervelocity, supercavitating projectiles fired from a conventional 20-mm gun mounted on a helicopter to rapidly neutralize near-surface moored mines. Major system attributes to be developed and demonstrated include algorithms for accurate LIDAR system targeting and fire control, projectile ballistic stability in both air and water, and projectile payload to ensure mine destruction with positive indication. For more information contact **Mr. Steve Collignon**, ONR 32CM, on 703-696-3039; e-mail colligs@onr.navy.mil

Multi-Spectral Optical Imaging

The multi-spectral imaging project is assessing the feasiblity of detection and identifying mines based on fluorescence spectra. Modifications to an existing laser line scan system will allow the simultaneous measurement of backscatter and fluorescence. Analysis of test results will permit the development of algorithms to interpret fluorescent signals and system specifications for optimum filter locations as a function of illumination wavelength. For more information contact **Dr. Steven Ackleson**, ONR 322, on 703-696-4732; e-mail ackless@onr.navy.mil

Joint Countermine Advanced Concept Technology Demonstration (ACTD) (Continued)

Airborne Standoff Minefield Detection System (ASTAMIDS)

System function: The ASTAMIDS will provide the capability to detect and identify the boundaries of patterned and scatterable anti-tank minefields such that the maneuver element commander can incorporate relevant threat minefield data into his operational planning. ASTAMIDS must detect mines/minefields consisting of metallic and nonmetallic surfaces, patterned buried, patterned surface scatterable mines and buried nuisance mines.

Description: The ASTAMIDS consists of an airborne imaging sensor and a minefield detection algorithm and processor which is a high-speed processor and minefield detection algorithm suite used to process sensor imagery and autonomously detect minefields. For more information contact PM-MCD/**Mr. Phil Purdy** on 703-704-1970.

Army Classified Program (ACP) For more information contact CECOM RDEC/**Dr. David Lee** on 703-704-1063.

The Importance of Keeping Historical Records Available in Mine Warfare

Dr. Tamara A. Smith

Picture if you will, a bird's eye view of a riverine squadron winding their way precariously up a mined river in interior combat operations in hostile territory. The shoreline of the narrow, twisted river is lined with dense foliage. Leading the fleet is a heavily-armed monitor, the riverine version of a battleship, armed with mine-avoidance and protection equipment, and capable of withstanding many different types of enemy attacks. Following astern are minesweepers, followed by gunboats, their guns trained at an invisible enemy ashore, their decks crammed with landing parties of three services. In support of this squadron fly the Cavalry, beating the bushes to expose guerilla raiders, contact mine operators, and snipers planning to waylay the invading fleet. As you picture this fleet proceeding up river, you can easily spot the narrowest, most tortuous passes ahead, those that could be most easily mined in anticipation of their arrival.

There are several documents which describe such a scene in detail. Some are sketches by on-scene observers, as well as detailed battle reports submitted to the government by the Union Navy in describing riverine operations in the Civil War of the 1860s. Replace the Cavalry horses with aircraft, and this scene is exactly recreated in similar detail in photographs, books, and memoirs of the riverine war in Vietnam in the late 1960s. In fact, putting an etching of the overhead view of a riverine assault in 1864 side-by-side with an aviation photograph of a similar expedition over 100 years later, as some authors have done, is the most eerily prescient reminder of an undeniable truth in mine warfare: **if you assume we**

will never come this way again, you will live to be proven wrong.

History does not repeat itself; but people often do. Our nation will, in future, continue to fight wars on open oceans, interior rivers, and the narrow passageways between nations. Sometime in future, our children and grandchildren will have to worry about defending their own shores, landing their troops on an enemy-held beach, or flanking a formidable foe by sea. While budget constraints restrain active planning to foreseeable options, there should be nothing which restrains us from keeping the lessons of our past alive and viable for the future. The words of the Vietnam veterans of riverine warfare who wrote about their wrenching and deadly experiences and came back to study both the past and the present, should haunt us. No longer should we ever read the words, "why didn't we learn those lessons 100 years ago?"

For several years, I had the opportunity to freely study the history and current operations of mine warfare as a part of my regular duties as a Navy Department historian, as a professor at the Naval War College, and as a researcher funded by the Commander, Mine Warfare Command. During that time I produced a book and some articles on the history of mine warfare, deployed three times to document mine warfare operations in Operations Earnest Will and Desert Storm, and conducted interviews, research and writing for a future publication on the history of Desert Storm mine warfare.

Along the way, I have learned some lessons about mine warfare which pertain to all future studies, technical, tactical, and operational. The first is, of course, that we should never assume that old requirements won't be needed again. We have ample evidence that it is in our national interest to assume that our future naval forces will require surface mine warfare ships, aircraft, training and technologies we have found useful in the past, and to be certain

that the operational requirements from the actual minefield experience of our forces are codified and available for future planners.

Second, mine warfare has depended for its entire history on the efforts of individuals to keep it a viable option. We recognize today that situation is unworkable. Current worldwide emphasis on the landmine situation has recently brought that problem into the public consciousness, although the effect of sea mines on ships in the 1980s and 1990s has already been erased from public view. The solution to keeping all mine warfare areas from declining in capabilities must be, in part, to keep it from becoming handed back to individuals within each service to solve. If there is one "Mr. Mine Warfare" in each service, I can assure you, from the vantage point of the study of 200 years of our history, it will revert to an individual person's problem. "Mine Avoidance" by ships and "Mine Warfare Avoidance" by Naval personnel, stem historically from this same focus on individuality.

Third, we don't know that much about our successes. Exactly why were our amphibious landings in the Pacific in World War II so successful? How did we successfully avoid the painful lessons learned at Wonsan, Korea, in the following two years of mine clearance during that war? How effective were helicopters in mine clearance at Haiphong? How did U.S. and allied mine warfare forces keep shipping lanes clear during Earnest Will and assist in operations resulting in a cease fire in Desert Storm? I have touched on all of these topics in my book, "Damn the Torpedoes," which is out of print, (but which is still regularly plagiarized from in student papers and in naval publications) but only to point out how valuable more detailed studies of these operations would be. We have in the bookstores today, self-help books entitled "Don't Know Much About History," and "Don't Know Much

About the Civil War." My book on mine warfare probably should have had a similar title. What is needed now is more in-depth, technical study of those elements of mine warfare of the past.

Fourth, so much information is available in the world press that our declassification efforts, the product of the perceptions of the Cold War, are largely outdated. We need to release more information on mine warfare to scholarly study than is currently being done. For example, no one can properly understand the decisions made during Desert Shield and Desert Storm in regard to mine warfare unless they understand the purported capabilities of the illusive Iraqi Sigeel mine, against which most planning was predicated. My own work which has survived declassification to date allows me to mention the Sigeel, but not to say anything about it. If we can't openly discuss a mine that may never have even existed, we will never fully comprehend and disseminate the circumstances under which our forces actually operated in Desert Storm.

Fifth, such dissemination of knowledge is the most crucial aspect required to fully integrate mine warfare as a regular, daily part of the operations of the U.S. military. The lack of true understanding and communication of mine warfare requirements throughout the Navy was the biggest failure of our naval mine warfare efforts in Desert Storm, and kept our forces from being fully utilized to the true extent of their capabilities. We cannot combat lack of knowledge of mine warfare in all of our services without emphasizing mine warfare education and better communication up and down the chain of command as a matter of priority.

I suggested in my earlier talk during this conference that the most effective solution to meet all these challenges is the establishment of a centralized facility for access to the many

scholarly mine warfare studies and documents proliferating throughout the United States. By this, I do not mean to suggest that one office take on the task of housing all known mine warfare documentation, but that they act as the coordinator of document information flow for studies utilizing documents of historic and operational use in mine warfare. It has become apparent to me over the past two years through late-night calls from students at many Naval and Military activities and Colleges, shipboard personnel, Pentagon staffers and mine warfare officers that there must be a better way to keep everyone studying the problems of mine warfare informed of the location of various mine warfare documents or of the feasibility of obtaining sufficient research data on a specific topic rather than having them resort to calling an unemployed historian. The need for better access and communications within the mine warfare community and those studying it are crucial to ensure proper and accurate interpretation of any technical or historical data.

For those of you who have forgotten or who have never had access to my book, I'd like to end this talk with a few words about the future taken from my conclusions, written in 1991. In it, I recounted the advice of several mine warriors over the years calling for a number of changes in the way the Navy approaches Mine Warfare. I am glad to see, from the vantage point of 5 years, that several of these specific conclusions on how to reintegrate mine warfare back into naval warfare have been met. We now have a flag officer assigned as PEO Mine Warfare to keep track of programs in the Pentagon. We have altered the strictly advisory role of Commander, Mine Warfare Command, as it was in Desert Storm, to one of considerable power to reshape mine warfare funding and forces. We have begun building a mine warfare community of trained personnel through creation of new leadership billets and a

Center for Mine Warfare Excellence. We have focussed discussion on prevention of mining, jointness, and flexibility. We are combining forces to ready emerging technologies and to rethink existing ones. Most important, we have stopped making mine countermeasures look so darned easy that bureaucrats can continue to assume that it can be accomplished without proper platforms, funding, doctrine, planning, personnel and training.

There remains much to be done. I have written about many mine warfare "heroes" whose work left a legacy upon which future mine warriors were able to build. One particular example stands out in my estimation. Those are the unnamed people who, during the devastating budget crises and downsizing of the Navy after World War II, still managed to leave behind complex and compelling documents requiring considerable study and foresight. These were the studies of the status of mine warfare at war's end, and the outlined improvements which could be achieved. The best were the planning documents for the next class of ocean-going surface MCM ships, requirements derived from combat mine countermeasures experience. The existence of this particular document became crucial a few years later when the disaster at Wonsan forced immediate production of such ships long after pundits proclaimed them unnecessary for future of the Navy. This is how we got one of the most capable and long-lasting ships ever in the naval service, the MSO, designed from the operational experience of two wars, which served as our main surface platform for over a generation.

I'm going to close this talk by reading the final two paragraphs of my conclusion, which I believe is still relevant today:

"The central problem of MCM throughout history has been the difficulty of sustaining

maximum capability over time. By its very nature, MCM evolves as the result of new mine developments and changing threats. Yet, in the U.S. Navy mine countermeasures have often been quick-fix solutions. Due to real competing needs, priorities, and lack of mine warfare knowledge within the Navy, it has been impossible to sustain adequate priority and funding for MCM. Important lessons learned, even when published by the participants, have been quickly forgotten, and subsequent attempts to revitalize the service have often been predicated on the wrong lessons. To date, no Chief of Naval Operations, Congress, or President has been opposed to an effective mine warfare program, and some have actively championed one. Yet, without historical perspective, recurring attempts to find an answer to the problem of an adequate MCM capability will continue to fail.

Lack of overall mine consciousness has often led us to remember the wrong lessons from our mine warfare experience. The recent minings of Samuel B. Roberts, Tripoli, and Princeton remind us that even our most valuable and expensive warships can be easily stopped by simple, cheap mines. When the Navy as a whole learns more about the reality and potential of mines and their countermeasures, MCM will no longer be called the Cinderella of the service and considered a subject about which much is written and less done. Only knowledge will end the legends and reveal the truth about men like Farragut, who only 'damned' the torpedoes by actively hunting them to determine the risk."

Naval Countermine Requirements

MAJ GEN John E. Rhodes, USMC
Deputy Commanding General
Marine Corps Combat Development Command

- Good afternoon ladies and gentlemen. I appreciate the opportunity to address this distinguished group on a topic of such significance to our armed services.
- My comments will focus on the capabilities that we feel are vital to support our emerging naval concepts; the warfighting concepts that will become reality in the 21st century.

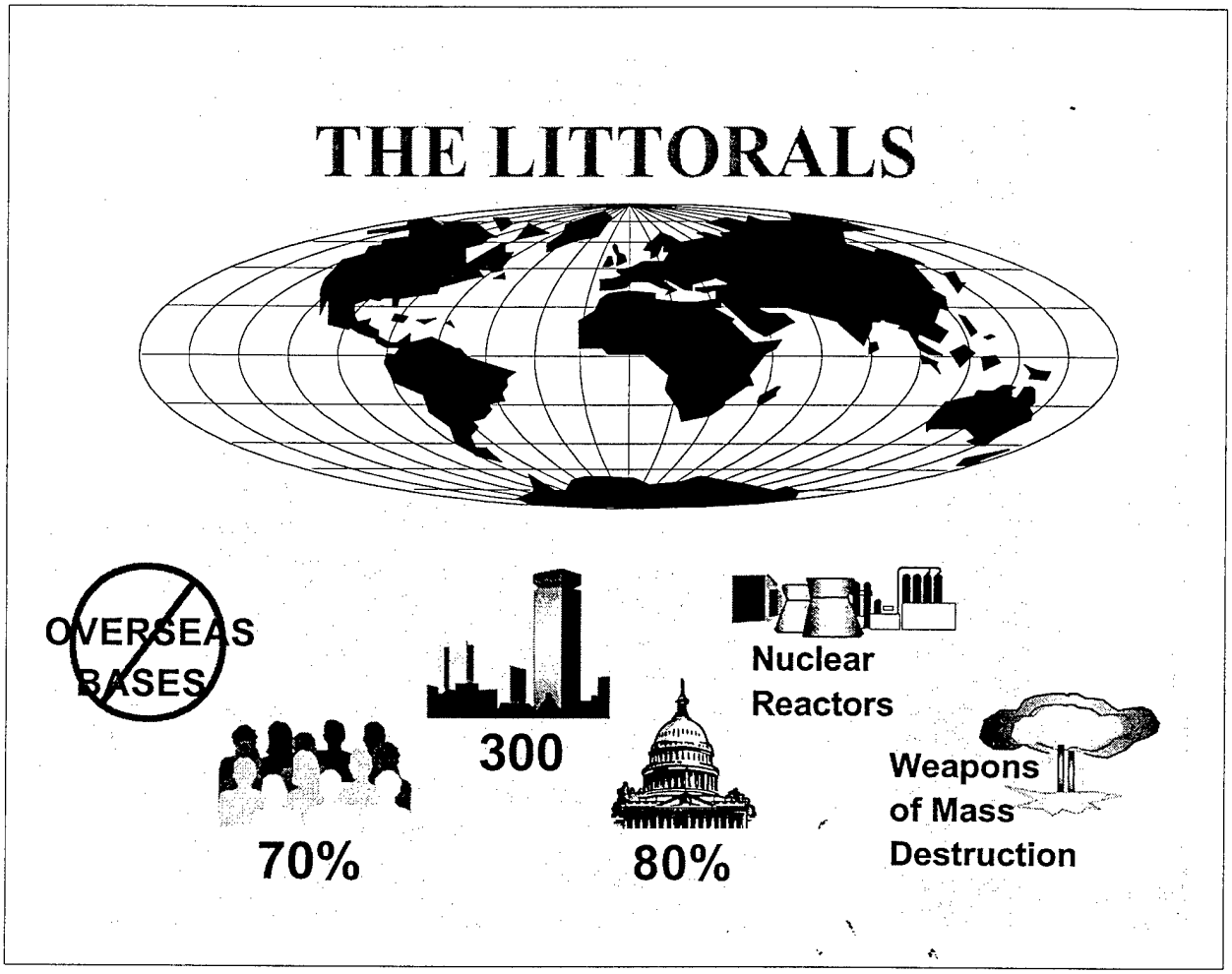


- (" . . . War is a violent clash . . .) While we will continue to be distracted by lesser conflicts, our preparation for war is the unifying thread on which we base our plans for the future. Future wars will be no less intense and no less violent - indeed, the ferocity of future conflicts may actually be enhanced by technological advances. Our greatest enemies may be those who think that the nature of war has or will change - it has not, nor will it. We must be prepared with flexible, multi-purpose forces that can fight and win the nation's wars.

War means fightin', and fightin' means killin'

- Nathan Bedford Forrest, CSA





- Of particular relevance to the Navy and Marine Corps is the emerging importance of the Littorals of the world as an operating environment. The reduction in overseas bases means that increasingly Naval Forces will be relied upon to be on-scene and ready to deal with emerging crises. Further, 70 percent of the world's population, 300 of its largest cities, 80 percent of its capitals and virtually all its nuclear reactors and weapons of mass destruction are located within striking distance of the littorals.

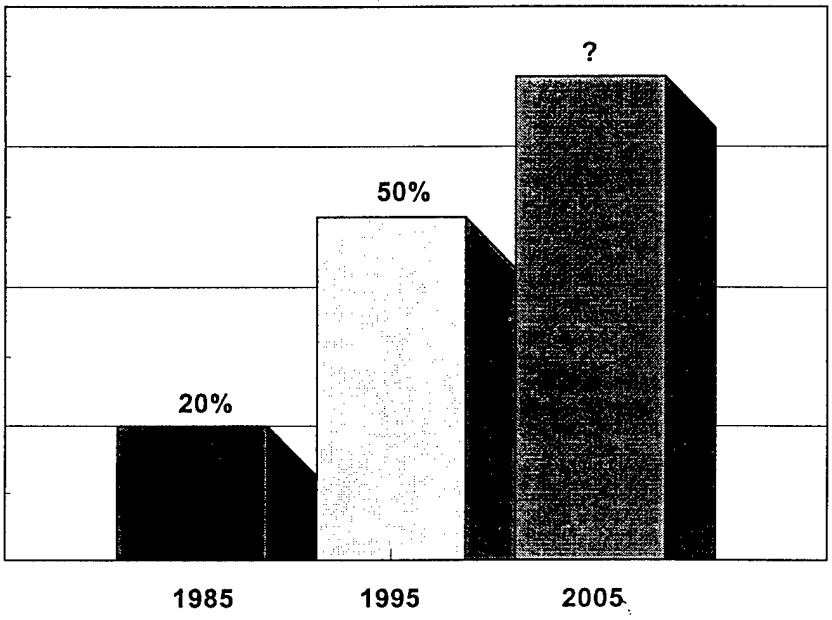
POPULATION IN THE LITTORALS



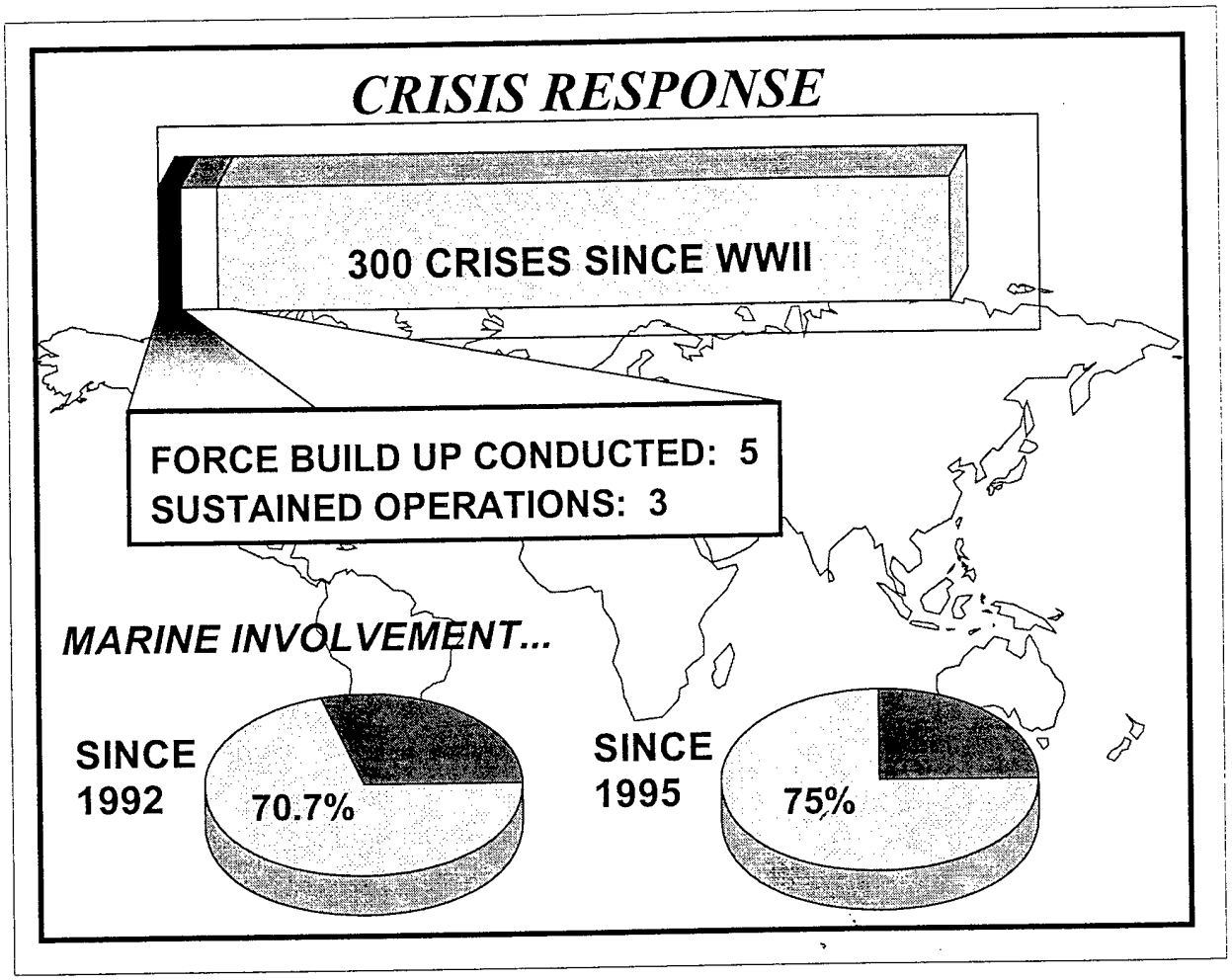
- This then, in our estimation, is the battle ground of the near future - it is crowded, urban, and accessible "From the sea . . ."

"Ten years ago 20 percent of presence missions were conducted by Naval forces, today it's 50 percent".

- Adm W. A. Owens

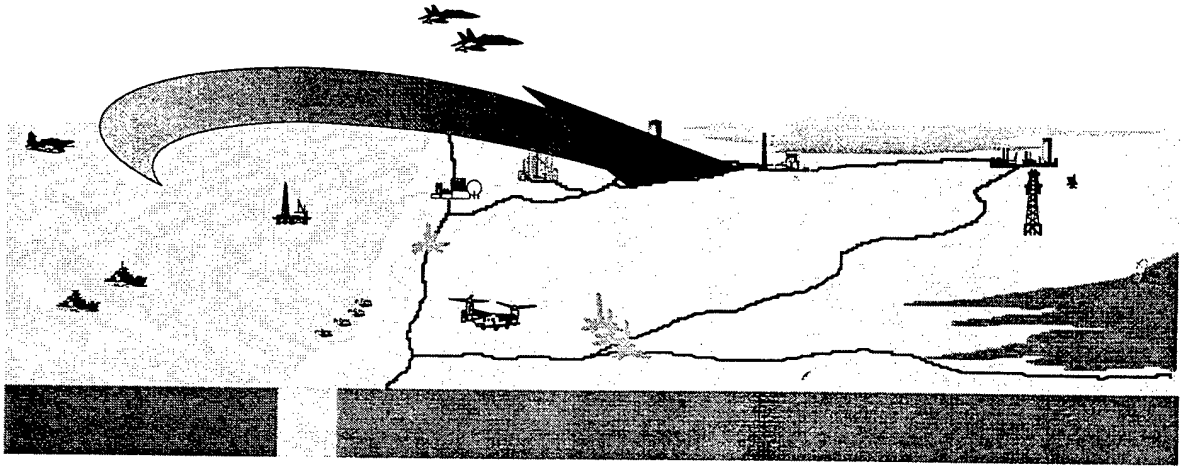


- As was noted by Admiral Owens, the nation's dependence on Naval forces has increased significantly and we expect that this trend will continue.



- Since WWII:
  - 300 Crises requiring U.S. resonse
  - Only 5 required force build-up beyond forward deployed forces (NATO, Korea, Cuban Missile Crisis, Vietnam, Desert Storm)
  - Only 3 required deployment of war termination forces (Korea, Vietnam, Desert Storm)
- 27 CVBGs and ARGs forward deployed since 1992 (Average deployment 180 days)
- Average number of Marines deployed is 24,000
- Since 1992, Marines have been involved in 29 of 41 operations (70.7%);since 1995, 18 of 24 (75%).

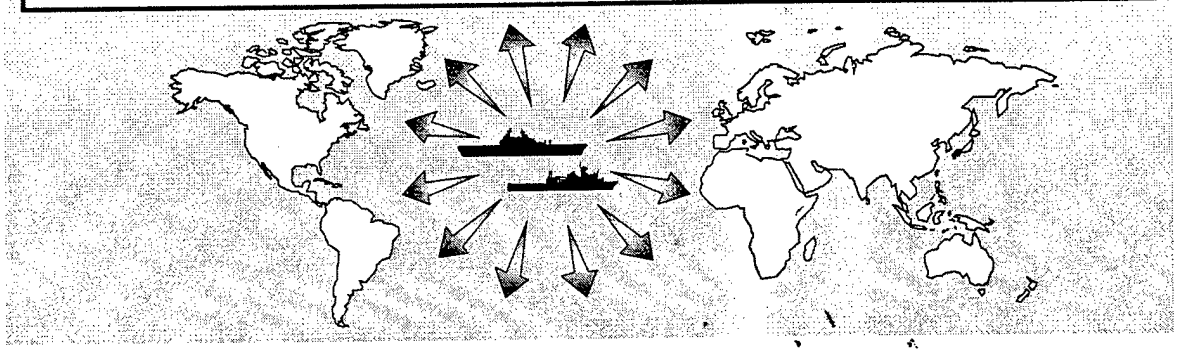
Operational Maneuver from the Sea (OMFTS) is a marriage between maneuver warfare and naval warfare . . . [It] will couple doctrine with technological advances in speed, mobility, fire support, communications, and navigation to identify and exploit enemy weaknesses across the entire spectrum of conflict.



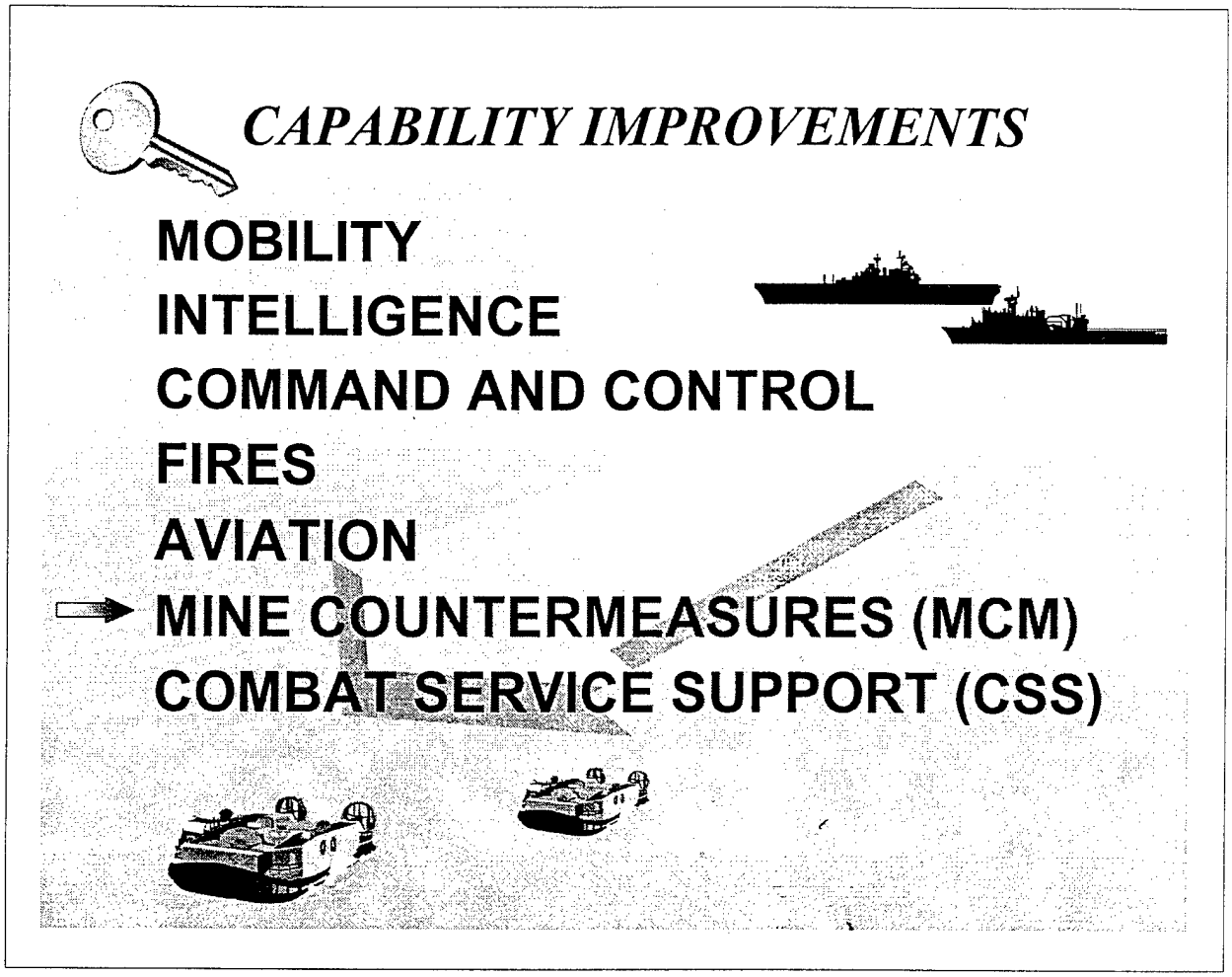
- The center piece of our preparations for the future is an approach to expeditionary, littoral, and amphibious warfare known as Operational Maneuver From The Sea (OMFTS). The heart of OMFTS is the maneuver of naval forces at the operational level in a bold bid for victory that aims at exploiting a significant weakness in order to deal a decisive blow.

TENETS OF OMFTS

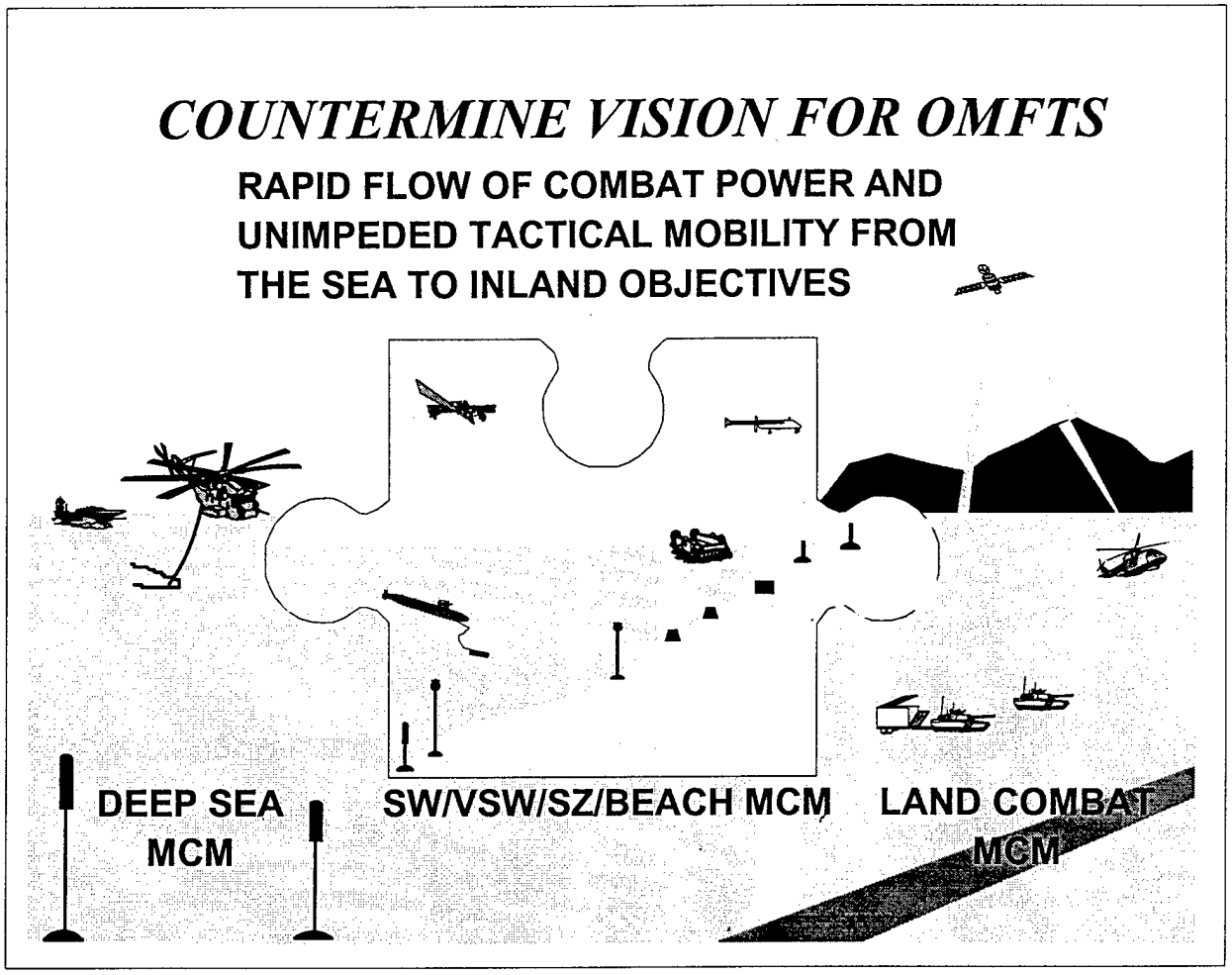
- FOCUS ON OPERATIONAL OBJECTIVE
- ACHIEVE VITAL OBJECTIVES RAPIDLY AND DECISIVELY
- CONTROL THE BATTLESPACE
- GENERATE OPERATIONAL TEMPO OVERWHELMING TO THE ENEMY
- EXPLOIT GAPS, WEAKNESSES, AND OPPORTUNITIES



- OMFTS focuses on an operational objectives and uses the sea as maneuver space. We will generate overwhelming tempo and momentum while pitting our strength against critical enemy weakness. OMFTS emphasizes intelligence, deception, and momentum while integrating all organic, joint, and combined forces.



- OMFTS will require us to overcome challenges in the areas of battlefield mobility, intelligence, command and control, fire support, aviation, mine countermeasures, and logistics. As OMFTS evolves conceptually, we will meet these challenges and find solutions using technology as well as new approaches in doctrine, organization, tactics, and training.
- Further, these capability improvements must be closely integrated. If any one category is allowed to lag behind the others, the full realization of OMFTS will be jeopardized.



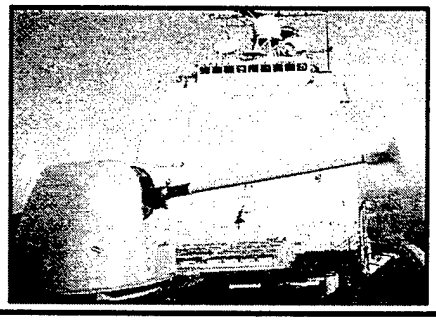
- Mine counter measures will clearly play a critical role in our ability to conduct OMFTS.
- Because of their relatively low cost and pervasiveness, mines have become a cheap means of limiting the mobility of ships and landing craft in contested littoral regions. For that reason, we are rapidly developing and enhancing our countermine and counter obstacle reconnaissance, marking and clearing capabilities; precision navigation; and in-stride breaching abilities to support maneuver at sea, the transition across the beach, and movement inland.
- Our deficiencies in mine counter measures can be considered the "long pole in the tent." We are looking to industry for the technological advances that will give us real time, seamless transition through a mined area.

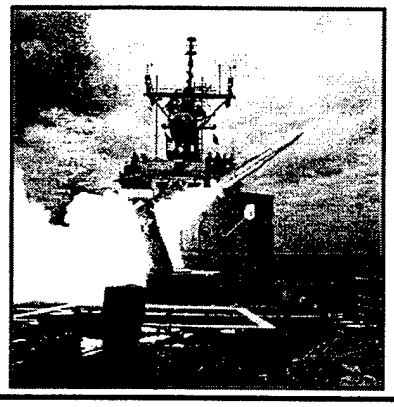
NEAR TERM REQUIREMENTS

- DOCTRINE & MINDSET THAT DOES NOT FOCUS ON *AVOIDANCE*
- TRAINING & EDUCATION TO ENSURE EFFECTIVE PLANNING & EXECUTION OF MCM OPERATIONS
- SUFFICIENT FIRE SUPPORT TO SUPPRESS ENEMY POSITIONS AND ISOLATE LANDING AREA



ERGM

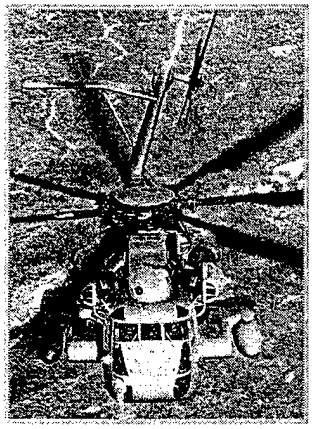


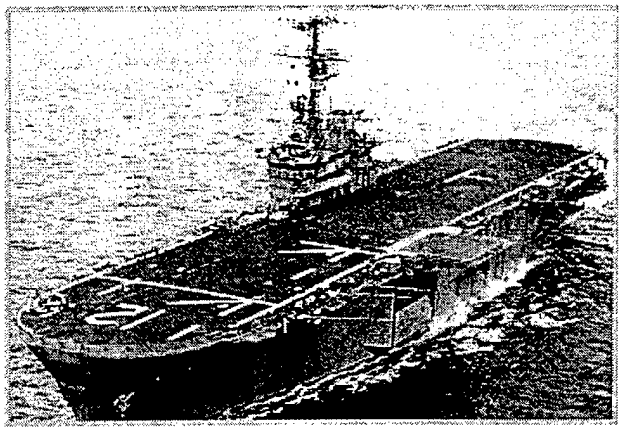


- We must first recognize and define the existing shortfalls in operational assets and practices.
- In developing our near term requirements, we seek to maximize our current capabilities and begin to develop the organizations, procedures, and equipment required to project power against littoral defenses and other mined areas.

NEAR TERM REQUIREMENTS (CONT'D.)

- **VERTICAL LIFT CAPABILITY TO MANEUVER SUFFICIENT FORCES TO HELP SECURE MCM AND SURFACE LANDING OPERATIONS (ADVANCE FORCE OPERATIONS)**
- **INTEGRATION OF MCM FORCES INTO POWER PROJECTION FORCE**

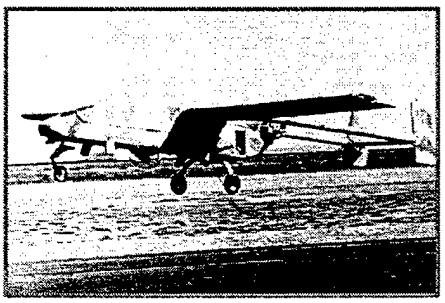




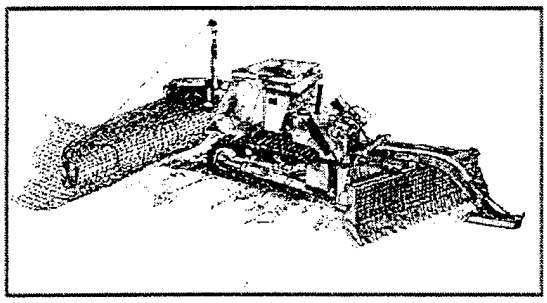
- We must first recognize and define the existing shortfalls in operational assets and practices.
- In developing our near term requirements, we seek to maximize our current capabilities and begin to develop the organizations, procedures, and equipment required to project power against littoral defenses and other mined areas.

MID TERM REQUIREMENTS

- IMPROVED CLANDESTINE MINE RECONNAISSANCE, PREPARATION, AND MARKING
- MORE RAPID LANE CLEARANCE CAPABILITY AGAINST MARITIME MINES OVER THE HORIZON
- RAPID DELIBERATE BREACHING CAPABILITY FROM SHALLOW WATER TO THE OBJECTIVE



COBRA ABOARD PIONEER UAV

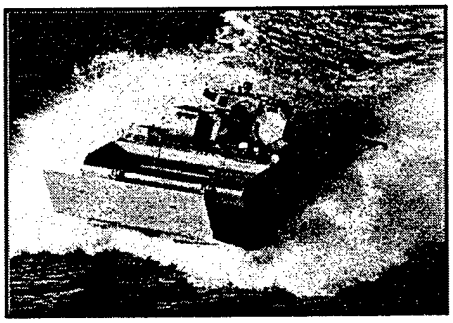


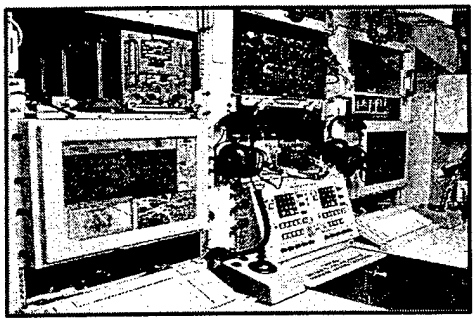
JOINT AMPHIBIOUS MINE COUNTERMEASURES

- The introduction of new technology will improve the potential for operational surprise, reduce the need for extensive suppression, and invest those resources toward exploiting the successful assault.
- Several specific requirements are listed that will guide our intermediate term combat development efforts.

MID TERM REQUIREMENTS (CONT'D.)

- AMPHIBIOUS FIGHTING VEHICLES CAPABLE OF HIGH SPEED, MULTIPLE OPTION SHIP TO OBJECTIVE MANEUVER
- ENHANCED, RESPONSIVE LETHAL & NON-LETHAL FIRES
- IMPROVED C4I INTEGRATION OF MCM AND POWER PROJECTION FORCES WITHIN OVERALL COMMAND STRUCTURE

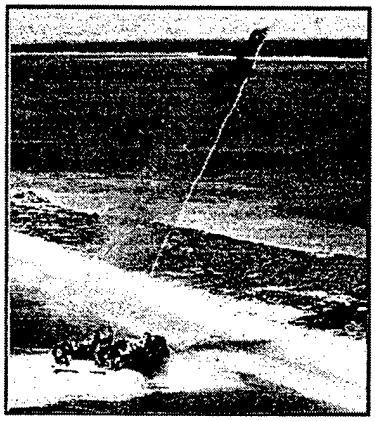




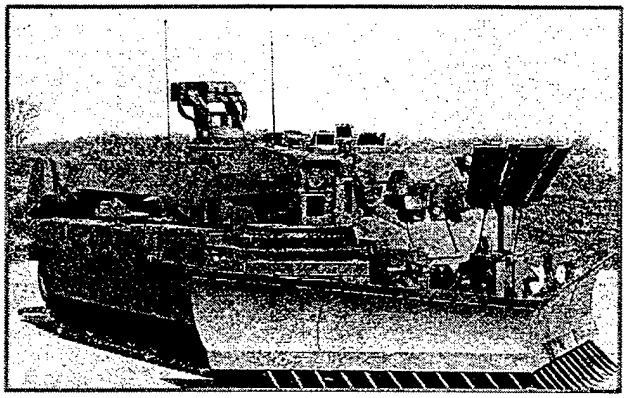
- The introduction of new technology will improve the potential for operational surprise, reduce the need for extensive suppression, and invest those resources toward exploiting the successful assault.
- Several specific requirements are listed that will guide our intermediate term combat development efforts.

FAR TERM REQUIREMENTS

- **IN-STRIDE MINE NEUTRALIZATION CAPABILITY FROM SHIPS AT SEA THROUGH INLAND OBJECTIVES**
- **ORGANIC IN-STRIDE BREACHING CAPABILITY WITHIN ASSAULT WAVES**



SABRE LAUNCHED FROM LCAC

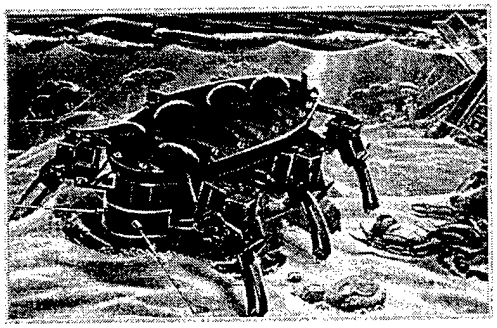


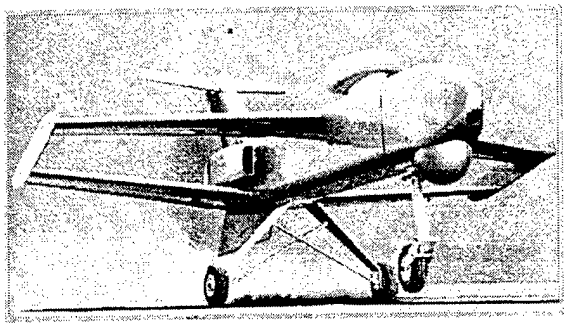
"GRIZZLY" COMBAT BREACHER VEHICLE

- Beyond the capabilities developed in the intermediate term concept, these additional improvements will significantly increase the flexibility and tempo of amphibious and expeditionary operations.

FAR TERM REQUIREMENTS (CONT'D)

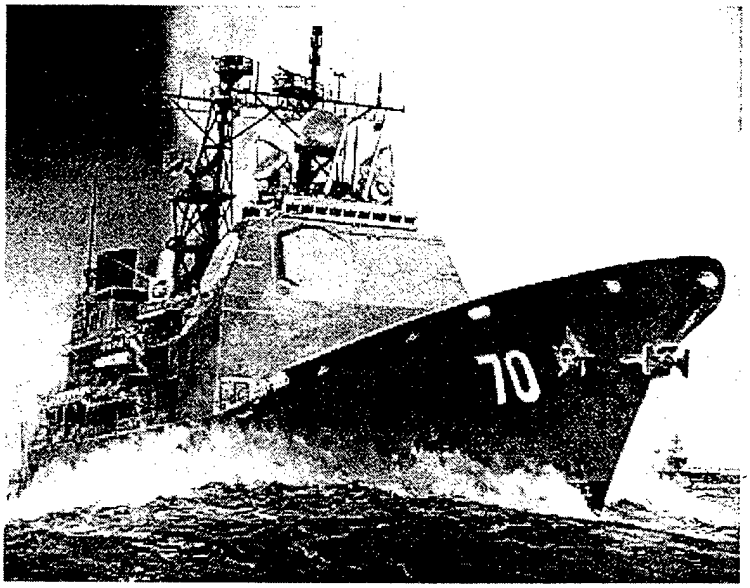
- CLANDESTINE RECONNAISSANCE CAPABILITIES FOR ALL LOCATIONS AND BARRIER TYPES
- ELIMINATION OF MINES AS A THREAT TO POWER PROJECTION FORCES THROUGH DESTRUCTION, REMOVAL, POSITION RECORDING, OR OTHER MEANS
- COMPLETE INTEGRATION OF MCM AND POWER PROJECTION FORCES





- Beyond the capabilities developed in the intermediate term concept, these additional improvements will significantly increase the flexibility and tempo of amphibious and expeditionary operations.

"...WHEN YOU CAN'T GO WHERE YOU WANT TO, WHEN YOU WANT TO, YOU HAVEN'T GOT COMMAND OF THE SEA. COMMAND OF THE SEA IS THE BEDROCK FOR ALL OUR WAR PLANS..."



- CNO, Admiral Forrest Sherman, following the Oct. 1950 Wonson, Korea mine crisis

- Mine countermeasures, both sea and land, are critical to the development of Operational Maneuver from the Sea and the ability of our armed forces to protect the vital interests of this nation.
- Only through properly focused technological development and thoroughly coordinated doctrinal refinement will the Navy-Marine Corps team effectively meet the challenges of the mined battlefields of the 21st century.

CHAPTER 3: OPERATIONAL ENVIRONMENTS AND THREATS

This Chapter presents papers on the nature of the mine threat, both on land and at sea. As the presentation by Major Colin King demonstrates, it is impossible to separate the explosive device, the mine, from the physical environment in which it is employed.

Participants' ideas about what the littoral environment is like were given added clariity at the Session at the Monterey Bay Aquarium, where attendees were privileged to hear from the Oceanographer of the Navy and from operational personnel involved with very shallow water mine countermeasures.

The Mining and Mine Threats Session then raised awareness of the magnitude and complexity of the problem presented by the mine threat. Major King, in his graphic presentation on mine clearance in the real world, showed vivid visual examples from personal experience in situations encountered in the Falklands, Afghanistan, Cambodia and Bosnia. "Hap" Hambric re-emphasizd the landmine dangers and demonstrated how new technology, combined with ingenious reinvention of existing technology, results in immediately fieldable, pragmatic solutions. Terry Kasey discussed the commercial foundations of landmine proliferation and reminded the audience that the sea mine problem is no less of a challenge. Finally, Prof. John Arquilla presented a solution which may lessen the need for stationary landmines altogether -- using mobile, responsive, armed unmanned vehicles to at least partially replace the military need for landmines used in their convention roles as means of delay and diversion (because of its autonomous systems element, his paper appears in Chapter 5).

MINE CLEARANCE .... IN THE *REAL* WORLD

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INTRODUCTION

A great deal of attention has recently focused on the problem of landmine proliferation and the problems involved in clearing minefields. Yet few people truly understand the nature of the threat and why, in an age of high technology and innovation, minefields should be so very difficult to clear. The landmine is firmly established as one of the most versatile and cost-effective weapons available. Unfortunately, the very characteristics that make it a success also make the mine extremely difficult to counter. To help explain the problem, this paper will highlight some of the characteristics of minefields and the mines they may contain. It is the vast number of possible permutations that prevents a "silver bullet" solution.

Aim

Let me start off by saying what I am *not* aiming to do: I would consider I had failed if anything I said were to discourage a promising line of new research. We must accept that all of the technology that we use on a daily basis began in the laboratory - sometimes with no promise of a practical application.

What I *do* intend to achieve is to give an overview of the real world problems to be considered when a new technology is being evaluated for field use. When I first discussed this presentation with Professor Al Bottoms (the conference organiser), he said that it might help to "keep us honest", meaning that it is all too easy to ignore (or be ignorant of) the real world problems when looking at alternatives for mine clearance.



Fig 1: A deminer training in Bosnia under ideal conditions. If real minefields looked like this there would not be a problem; unfortunately they don't.

The Current Situation

The most satisfactory solution would be to achieve mine clearance without the need for detection. This, in essence, is what the military seek to do with the use of flails, rollers, ploughs and explosive hoses. These rapid clearance expedients, which do not require the individual detection of mines, have already been copied and adapted for civilian use for many years. But in military use, they are intended only to "breach" a path through a minefield in the shortest possible time, with a corresponding compromise in thoroughness. There are specific applications, such as the clearance or proving of routes, where such equipment can be highly effective; but these are the exceptions rather than the rule.

All over the world, every day, areas of mines

are being cleared manually using probes and locators. Although new technology and equipment is tried from time to time, and used within limited appropriate applications, operation managers have little time for rapid clearance techniques. Their job is to ensure, to the very highest level of confidence, that their area is totally clear of mines when it has been swept. In the vast majority of circumstances, mechanical clearance simply cannot achieve this. Manual clearance is currently the only solution: this requires each mine to be detected by probing and metal detection, and then disarmed and removed or destroyed in place.

Mine clearance project managers believe that many researchers do not understand the process that is used, or the reasons that no alternative currently exists. As the manager of the Bosnian Mine Action Centre says:

"Unless you understand the process, how can you find ways to improve upon it?"

MINEFIELDS

General

Minefields come in a variety of guises and sizes, but they are rarely the flat, uninterrupted grassy plains where so many of the demonstrations and publicity shots take place. Even ignoring the special circumstances of Kuwait's oil lakes or the Falklands drifting sand dunes, minefields are never simple. When considering the following scenarios (which are by no means comprehensive) it must be remembered that they often appear in combination. In the Falklands, for instance, there are steep, rocky slopes with grassy patches, crossed by streams and littered with shrapnel and unexploded ordnance.

Grassland

To begin with, where mines *are* laid in fields or open grassland (eg. the Falklands), grazing animals do not keep it short and the grass soon reverts to a wild state, overgrowing mines and normally forming uneven tussocks. In many parts of the world flat grassland has waterways cutting through it, and may be too soft to support heavy mechanical equipment. Whenever water passes through a mined area there is a constant danger of mines being moved about, possibly moving several miles downstream. This is a regular occurrence in the Falklands, and a major concern in Cambodia, where much of the ground is covered by water for long periods each year. Standing water renders most detection techniques useless and often prevents any form of mine clearance. Much of the grassland in former Yugoslavia is also covered by snow for several months of the year: this too prevents the effective use of most detection and clearance techniques.

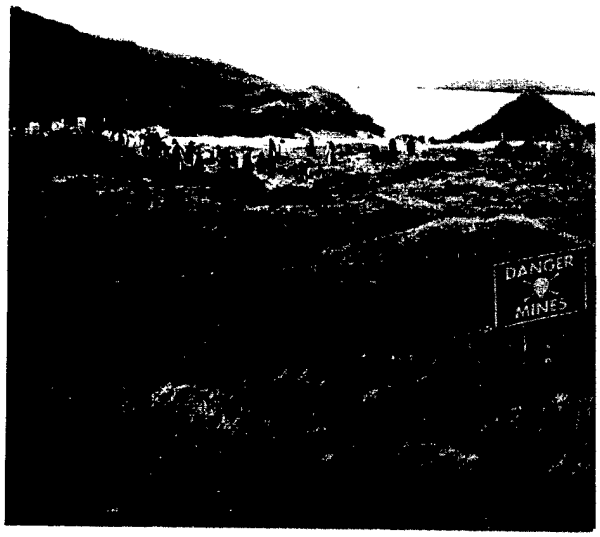


Fig 2: Mined areas of grassland soon revert to a wild state, hiding mines. Water moves mines and often softens the ground too much to support heavy equipment.

Vegetation

Many of the minefields in former Yugoslavia, Africa and South East Asia contain dense vegetation which has often been established for several years. In many cases the tangled foliage simply prevents any access or view into the mined area; where it has grown up around tripwires, the situation is particularly difficult.

Unless the vegetation can be safely burned away, deminers are faced with the prospect of clipping and removing each twig individually. Dense vegetation containing small trees totally

prevents the use of most mechanical expedients.



Fig 3: Dense vegetation will totally defeat most mechanical equipment and conceals tripwires. It makes progress painfully slow.

Rocks

Rocky soil is also a problem in many parts of the world. Small stones can make probing almost impossible while larger rocks can interfere with detection techniques and prevent the use of ploughs or flails.



Fig 4: The steep rocky terrain found in Afghanistan and the Falklands (above) also prevents the use of most heavy mechanical equipment.

Stony sand and rocks caused major problems during the clearance of some beaches in Kuwait where mechanical clearance could not be used: manual techniques became extremely dangerous and one British operator was killed whilst trying to uncover a mine in these conditions. Terrain with steep slopes and large outcrops of rock, common in Afghanistan and the Falklands, clearly makes the use of any vehicle-borne system impractical.

Battle Areas

Not surprisingly, mines are often found in areas where battles have been fought, contaminating the ground with the scrap of war. At least, there are bound to be large quantities of metal present: one shell can produce thousands of steel fragments, each large enough to dwarf the signature from a minimum-metal mine. At worst, the area may be criss-crossed with barbed wire and the guidance wires from missiles, cratered and littered with unexploded ordnance (UXO).



Fig 5: Battlefield scrap from the Gulf War. Metal fragments mask the signature of mines, while unexploded munitions present additional hazards.

The failure rate among conventional munitions is generally around 10%, and may be far higher. This means that the quantity of UXO can sometimes exceed the number of mines, as was the case in the "Rockeye" submunition strikes in the Persian Gulf, where large numbers failed to function. Although most types of UXO are less hazardous than mines

this is not always the case - particularly with submunitions. Once armed, unexploded dual purpose bomblets such as the American M42 or the Yugoslav KB-1 are far more pressure sensitive than any AP mine.

Urban Areas

When considering "cluttered" environments, it is easy to overlook the fact that mines and booby traps are also used in urban areas. Clearance of houses and surrounding ground, for instance in former Yugoslavia and Afghanistan, can be a very slow and complex process. In most cases the presence of buildings, walls, fences, paths and roads makes the use of mechanical equipment impossible, and detection techniques are hampered by the large quantities of metal present.

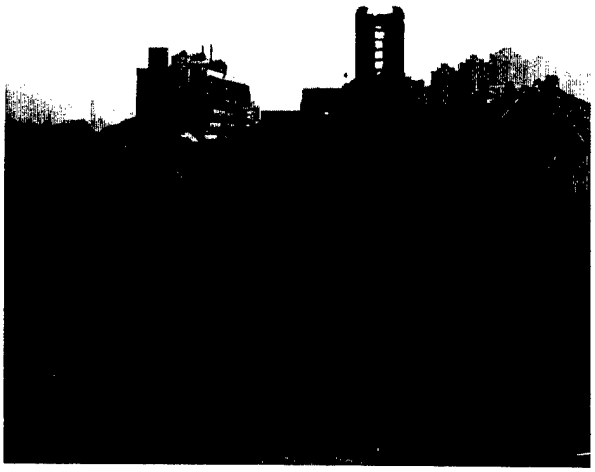


Fig 6: Urban areas containing mines and booby traps present special problems. Clearance sometimes begins to resemble counter-terrorist search operation.

Inside buildings, where virtually any type of booby trap may have been used, the clearance procedures are often similar to those used in a counter terrorist environment such as Northern Ireland. This type of house clearance is painfully slow and very dangerous.

THE MINES THREAT

When people mentally picture a landmine, they tend to think of a pressure-operated blast mine - probably plastic - buried in an open, flat, grassy or sandy area. Of course there are a large number of different types of mine, and they are rarely presented in such ideal circumstances

Blast Mines

Pressure operated mines, both anti-personnel (AP) and anti-tank (AT) are indeed often plastic cased; many have a minimal metal content that makes them extremely difficult to detect. Many are also "blast resistant" making them virtually immune to the effects of shock or explosive overpressure. Increasingly, these mines are scatterable and will therefore appear at irregular intervals on the ground - sometimes in quite dense clusters. Some have the explosive in the centre (such as the Yugoslav PMA-3), while others have a central fuze mechanism and a ring of explosive around the outside (like the Italian SB-33). Some, like the Russian PFM-1, contain liquid explosive.

Since simple pressure-operated mines are so easy to remove and disarm once they have been located, there is an increasing trend towards the use of electronically fuzed booby trap versions of existing mines. These mines (eg. the Chinese Type 72B) share the same casing as their conventional counterparts and cannot be visually distinguished from ordinary mines. Where these mines are used, manual mine clearance becomes even more hazardous to the operator.

Stake Mines

Stake mines (such as the Russian POM-Z and Yugoslav PMR-2A) are simple omnidirectional fragmentation mines, generally initiated using a tripwire. Despite the fact that they are used all over the world, the problems that they present are rarely addressed in clearance drills. Unlike blast mines, they have a significant safety distance - most can cause serious injury at over 100 m. When detonated, either accidentally or by demolition, the fragments further contaminate the surrounding area with

steel, causing false alarms on detectors. The explosive content of the mine is above the ground level and can be awkward to attack using standard explosive blocks.



Fig 7: The tripwires for stake mines, such as this Yugoslav PMR-2A, are often concealed by tangled vegetation. It is common practice to bury pressure-operated blast mines below tripwires to catch unwary deminers.

Bounding Mines

Bounding mines (like the Italian V-69 and the Yugoslav PROM-1) are generally buried in the ground and activated either by pressure or using a tripwire. When initiated, they jump 2 - 4 feet into the air before detonating: once again, they scatter steel fragments over the surrounding area and can injure at significant ranges. Although their high metallic content makes them simple to detect, tripwire-initiated bounding mines may kill or injure their victims some distance away from the mine's position.

The tripwires from bounding mines are normally closer to the ground than those of stake mines and are often totally concealed by vegetation. Many have the ability to use multiple tripwires running off in different directions. Because a tripwire could have a mine on either end, or may initiate a device when it is cut, taut wires must always be followed to both ends during manual clearance. It is common practice to bury blast mines under the path of the tripwire to catch unwary deminers.

Directional Fragmentation Mines

These mines use the detonation of high explosive to project shrapnel in a predetermined direction. The mines come in two basic types: the "Claymore" type rectangular mines (such as the US M18A1 and the Yugoslav MRUD) project their shrapnel in a horizontal fan, and can be lethal at over 50 m. The circular type (eg. the Russian MON-100) have an effect similar to a large shotgun, with a cone of fragments projected to ranges often exceeding 100 m.

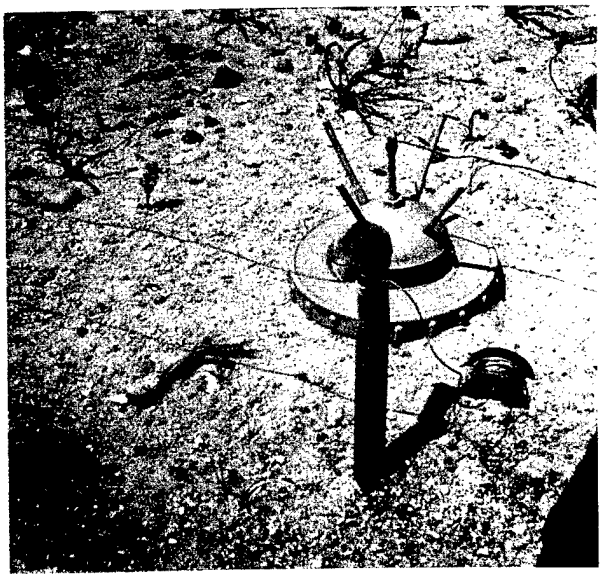


Fig 8: Although bounding mines such as this Italian V-69 are normally semi-buried, directional mines are often placed well above ground. Both have substantial danger zones and can contaminate large areas with steel fragments when initiated.

Directional mines are almost always placed *above* the ground to take maximum advantage of their range; in Bosnia they are often positioned high up on tree trunks, overlooking fields of buried mines. Most can be initiated either by electrical command or by tripwire, and the wire may also be several feet above the ground. Deminers must adopt a special procedure to destroy these mines in place when they are well above the ground, this can be clumsy and dangerous. Once again, detonation scatters fragments over a large area, making subsequent detector search far

more difficult.

AT Shaped Charge Mines
Modern AT mines are making increasing use of shaped charges to enable a small explosive charge to defeat vehicle armour. The most common principle is the use of a *Misznay Schardin* plate, which becomes a "self-forging fragment" (sometimes known as an "explosively formed projectile" or EFP) when the mine detonates. The Yugoslav TMRP-6, a mechanically laid shaped charge mine, can be electrically command detonated or operated by pressure or tilt-rod. The Misznay Schardin plate can also travel for a considerable distance, allowing it to be used horizontally as an off-route mine.

Scatterable shaped charge mines, like the US BLU-91/B "GATOR", generally incorporate a magnetic influence fuze. First-generation magnetic influence fuzes are often initiated by movement, giving the mine and inherent anti-disturbance function. GATOR is also fitted with a self-destruct feature, though this proved unreliable during the Gulf War.

Booby Traps
To further complicate the picture, virtually any mine can be booby trapped in a variety of different ways. In former Yugoslavia, World War 2 British and American mechanical booby trap switches are still in use, complemented by a range of ingenious, well-designed modern devices. The presence of booby traps further limits the number of techniques available to the deminer: for example, in Bosnia, buried mines must be uncovered with the greatest of care and always be pulled out of the ground remotely or destroyed in place. This makes the process of mine clearance even more dangerous and slow.

Electronic booby traps, which are also used in Former Yugoslavia, can operate on principles such as light, thermal or acoustic sensitivity, vibration, tilt, inertial, time delay or breakwire. In Bosnia, such booby traps have been found hidden inside AT mines, melted into the explosive. With such a formidable array of potential traps, it is almost impossible to devise universal manual mine clearance drills.

SHORTCOMINGS OF CURRENT CLEARANCE OPTIONS

Hand lifting and probing
Greatly complicated by hard stony ground, booby traps and anti-disturbance mines.

Metal detectors
Can be defeated by minimum-metal mines. Greatly complicated in ground heavily contaminated with shrapnel and scrap.

Flails
Can be defeated by resilient anti-shock mines. Defeated by barbed wire, thick vegetation and difficult terrain.

Rollers
Defeated by double impulse fuzes, careful positioning of mines, thick vegetation and difficult terrain.

Ploughs
Defeated by careful positioning of mines, thick vegetation and difficult terrain.

Explosives
Defeated by blast-resistant mines unless sympathetically detonated.

CONCLUSION

In summary, the mine is an inherently effective weapon normally characterised by simplicity, versatility, lack of discrimination and longevity. Considering that mines are generally victim operated, these features alone would complicate the task of mine clearance. But mines may be operated by pressure, tripwire, command and a variety of other influences. They can incorporate blast resistance, anti-disturbance and booby traps and may have virtually no metal content to aid

their detection. They can be used below, on, or above the ground; among rocks, thick vegetation, and in shallow water. Considering that any combination could be encountered in a single minefield, it is hardly surprising that there is no panacea.



Fig 9: The beaches of Kuwait with tripwire-operated V-69 bounding mines on stakes in the water and pressure operated VS-50 AP blast mines in the sand. A combination of large rocks, steel stakes, barbed wire and wet, stony sand ruled out everything except manual clearance. Just two types of simple mine in a typical battlefield setting: parts of Bosnia are far more complicated than this!

Gradually, it is dawning on the mine clearance community that a combination of different equipment and techniques are required, and that these must be closely tailored to the specific threat in each minefield. In combat situations this is rarely possible, and military minefield breaching accordingly tolerates the limitations of its rapid mine clearing expedients. Humanitarian demining can afford no such luxury and has generally had to rely upon the painstaking work of men equipped with locators and probes.

Operational mine clearance programme managers are constantly bombarded with suggestions and sales pitches, mostly for unusable techniques and equipment, by people with little or no understanding of the problem. There is a very real danger of these programme managers becoming so antagonised that even promising new technology is dismissed out of hand.

It is crucial that those working on new mine detection and clearance techniques take account of the real-world problems. Ideally, they should be familiar with the nature of the technical threat and the environment in which it exists in order to understand the process that is currently used for demining. In practice this is difficult to achieve without extensive operational experience; the obvious solution, therefore, is to bring the demining community together with the researchers. Without this symbiosis, scarce resources will be wasted on unrealistic solutions that simply cannot address the problems of mine clearance in the real world.

Colin King

Major Colin King left the British Army after 14 years, but still undertakes operational work as the sole EOD analyst for the Ministry of Defence. His experience includes work in the Falklands, Gulf, Afghanistan, Cambodia, Croatia and Bosnia. He is a freelance consultant, and recently completed a detailed technical reference book entitled "Mines and Mine Clearance" for the Jane's Information Group.

THE ANTIPERSONNEL MINE THREAT

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ABSTRACT

Mines are a major threat in all types of combat and will be the major threat in Operations Other Than War (OOTW) which are expected to be the most likely missions for US forces in the future as well as post conflict humanitarian demining operations. Historically, mines have always comprised a large part of the total threat, and their share is increasing. The clear historical trend is that mines will be the dominant threat to the lives of US Army personnel in the future. The current worldwide proliferation and widespread employment of landmines threatens to neutralize US technological advantages in conventional conflicts. In these conflicts, mines are a threat to all US personnel (combat or support) who are employed within 25 to 50 km of the combat zone. In OOTW, the use of mines threatens the successful completion of such operations by creating unacceptable casualties which undercut popular support. In this situation, mines are a threat to any individual that operates outside of small, carefully secured areas.

The principal global threat consists of very large numbers of unsophisticated (but effective) mines and a virtually unlimited supply of improvised explosive devices which may be used in mine roles. These low tech mines are the expected threat in OOTW. A much smaller, but steadily increasing number of modern mines with advanced electronic fuzes are appearing in the inventories of conventional armies. Conflict with one of these forces is less probable, but in time, the electronic fuzed mines are certain to become a major problem for US personnel as they find their way into the hands of unconventional forces.

This paper will provide an overview of the antipersonnel (AP) mines available worldwide, and in doing so, outline the AP mine threat for the use of the countermine and demining communities. The numbers and varieties of mines will at first seem daunting, thus it must be emphasized that the mine threat can be effectively addressed through the development of appropriate technologies.

I. INTRODUCTION

The wide spread employment of landmines threatens to neutralize US advantages in firepower and mobility by severely limiting our ability to maneuver and disrupting our tactical synchronization.[1] Mines are a major threat in all types of combat operations and will be the major threat in most Operations Other Than War (OOTW). Mines directly attack the basis of our current doctrine by limiting our tactical maneuverability and slowing our operational tempo. Like chemical warfare, mines are part of the battlefield environment and effect everyone involved. Nonetheless, the US Army has fielded very little to counter the mine threat, while their fuzing, lethality, and emplacement technologies have continued to evolve.

The vulnerability of US personnel and tactical vehicles to even the most primitive mines has resulted in a significant number of American casualties in the last seventy years.[2] The rate of losses due to mines has been rising since WW I. Mines have caused almost 100,000 US Army casualties since 1942, enough manpower to create nearly seven infantry divisions. Mines have also knocked out an estimated 1,200 US Army tanks, enough to equip almost 5 WWII period armored divisions (Table 1 and Appendix A).

The threat posed by mines will only worsen as the worldwide proliferation of advanced landmines continues. Many mines currently being produced around the world are significantly more advanced than the current US inventory of conventional mines.[3] In addition to the mines being sold by former Warsaw Pact countries, several western and third world countries manufacture and export mines as well, some of which are quite advanced (Table 2).[4] The worldwide mine inventory is estimated to be several hundred million, with an estimated 2500 mine and fuze combinations and approximately 100 million emplaced.

Compared to other military technologies, countermine offers the Army the greatest payoffs in the areas of casualty reduction and increased battlefield mobility. To achieve these payoffs, the requirements writer/battle simulator must determine which mines constitute a significant threat to the force in question. Then the countermine designer must understand the nature of those mines and how to counter them.

TABLE 1: US ARMY MINE LOSS RATES[a]

THEATER	TANKS[b]	PERSONNEL[c]		
		KIA	WIA	TOTAL
WWI (1918)	(16%)	NA[d]	NA	NA
WWII (OVERALL)	23%	2.7%	5.1%	4.5%[b]
MEDITERRANEAN	29%	4.6%	5.9%	5.5%
WESTERN EUROPE	21%	2.4%	4.7%	4.1%
PACIFIC	33%	1.9%	1.9%	1.9%
KOREA	(56%)	4.5%	3.8%	3.9%
VIETNAM	(73%)	28%	34%	33%
PERSIAN GULF	60%	34%	(3.0%)	(10%)
SOMALIA	55%	25%	(6.6%)	(9.7%)
TOTAL	(24%)	6.0%	(11%)	(10%)

[a]( ) Indicates partial data set.
[b]Data taken from Appendix A, Table A-1, column (3).
[c]Data taken from Appendix A, Table A-1, columns (5), (7), & (9)
[d]NA indicates data "Not Available."

TABLE 2:
MAJOR PRODUCERS OF LANDMINES[6]

Former Soviet Union	Italy
Former Yugoslavia	France
China	United Kingdom
Czechoslovakia	Germany
Egypt*	United States
Singapore*	Belgium
Pakistan	Sweden

* Produces copies of mines developed elsewhere

II. MODERN MINE CHARACTERISTICS[7]

The last 50 years have witnessed significant advances in mine warfare technology and techniques (Table 3). See Appendix B for information on the origins of military mines. These are expected to continue rapidly evolving. Advanced electronic sensors and processors have been coupled with fragmenting mines to produce a highly lethal threat to dismounted personnel. The manufacturers of these electronically fuzed mines may also offer the option of remote control on/off, programmable self-destruct or self-neutralization, improved fragmentation, and long range emplacement systems.[8] Many countries have fielded mine technologies specifically designed to defeat our current countermine equipment and techniques. These include integral antihandling devices, anti-sweep fuzes, and very low-metallic content mines (which are extremely difficult to detect with today's metallic mine detectors). Blast resistant mines that are relatively immune to clearance by mine clearing line charges and other explosive means are also becoming more common.[9] Although the need for improved countermine technologies has become critical, the US has made little progress since WWII (Table 4).

TABLE 3: AP MINE TECHNOLOGY EVOLUTION

	US WWII MINES[10]	RECENT DEVELOPMENTS
FUZE	Simple Pressure	-Advanced electronic sensors and processors -Blast resistant
DETECTABILITY	Easy (metal case)	-Very difficult (very little metal)
CONTROL	None	-Remote control on/off -Programmable self destruct or self neutralization
EMPLACEMENT	Manual	-Wide variety of scattering or laying means
ANTIHANDLING	None	-Integral electronic -Electronic add-on

TABLE 4: US COUNTERMINE TECHNOLOGY EVOLUTION

	WWII (US)	CURRENT (US)
Detection	Visual, probes, metal detectors	Visual, probes, metal detectors
Mechanical Breaching	Rollers, flail	Plows, rollers, rakes
Explosive Breaching	Explosive line charge bangalore Torpedo	Explosive line charge bangalore Torpedo
Area Clearance	Flail, blow-in-place, manual	Blow-in-place, manual

In a counterinsurgency situation, AP mines can be found almost anywhere, but are typically laid without pattern along roads and trails, or as part of protective obstacles around a base camp. AP mines are the major threat in a low intensity conflict environment because of the high proportion of dismounted operations that must be conducted.[11] In a conventional, mid-intensity conflict, US combat engineers can expect to encounter them in tactical and protective minefields. AP mines have evolved into three general types: fragmentation, blast or chemical (Table 5).

FRAGMENTATION AP MINES

Modern, self-contained fragmenting AP mines were employed in the West in relatively small numbers during the American Civil War. However, they did not appear in significant numbers until World War II. From WWII, three types of fragmentation mines emerged: bounding mines, the predecessors to the M16 "Bouncing Betty"; directional mines, the predecessors to the M18 Claymore; or simple fragmenting, like the Soviet POMZ-2 stake mine. Fragmenting mines are intended to kill and particularly dangerous because they tend to cause multiple casualties when activated. When employed with

TABLE 5 : COMMON AP MINES

Origin	DIRECTIONAL	BOUNDING	SIMPLE FRAGMENTING	BLAST
US	M18	M16	M74	M14*
		ADAM/PDM	M3	
USSR	MON-200	OZM-3	POM-2	PMN-2
	MON-100	OZM-4	POMZ-2M	PMN
	MON-90	OZM-72	POMZ-2	PFM-1
	MON-50			PMD-6M
CZECH		PP-Mi-Sr	PP-Mi-Sk	PP-Mi-Ba
		PP-Mi-Sr II		PP-Mi-D
YUGO	MRUD	PROM-1	PMR-1	UDAR
		PROM-2	PMR-2	PMA-1
		PROM-KD	PMR-3	PMA-2
			PMR-4	PMA-3
ITALY	VS-DAFM 1	VALMARA 69	P-25	SB-33
		VS-SAPFM3		VS-MK2
		BM-85		VS-50
CHINA		TYPE 69	TYPE 58	TYPE 72A/B
			TYPE 59	
UK	PAD			RANGER
				C3
FRANCE	MAPED F1	M-1955	M-61	M-59
			M-63	M-1951
GERMANY	SM-70	DM-31	AP-2	PPM-2
		K-2		DM-11

* The M14 has been removed from US stockpiles.

trip wire fuzes, these mines have proven extremely effective, and their greater effective coverage enables the emplacing unit to get the same effect with significantly fewer mines per kilometer of front.

These highly lethal, area effect weapons have had their performance significantly increased through the use of advanced fuzing and the use of pre-fragmented casings. Advances in fuze technology, such as seismic influence and breakwire circuits, which can be found in some mines being fielded today will make them even more difficult to counter. For example, the Soviets have developed and fielded the VP series of mine control devices which are based on seismic influence and possess an advanced processor for target discrimination. These devices can be employed with five of either the MON and OZM series mines.[12] The VP series of devices were first employed in Afghanistan and have proven to be extremely effective. The Soviets and the French have also fielded breakwire fuzes. The breakwire fuze, which can be used with both directional and bounding AP mines, is based on a collapsing circuit. When the delicate wire is stepped on or cut, a circuit is broken, and the mine is activated.[13]

DIRECTIONAL MINES

The first directional AP mine to enter production, the M18 Claymore, first saw combat in Vietnam.[14] The Claymore has a lethal range[15] of 50 meters and covers a 60 degree arc. It is widely copied and is employed by many countries (Table 6). Two of the most effective directional mines currently in use are

the Soviet manufactured MON-100 and MON-200. They produce a kill zone with a 4 to 5 degree arc and an effective lethal range of 100 and 200 meters respectively. No other directional AP mine currently in use can match the ranges of the Soviet MON-200.[16] Among the important concerns for the countermine designer is the early detection and neutralization of approach hazards (tripwires, breakwires, seismic sensors, and command detonation) and ballistic survivability.

TABLE 6: COMMON DIRECTIONAL AP MINES

Origin	Mine	Fuze	Lethal Arc	Lethal Range	Explosive
US	M18	T,C	60	50m	682 g C-4
USSR	MON-200	T,C, B,S	4	200M	12kg TNT
	MON-100	T,C, B,S	5	100M	2kg TNT
	MON-90	T,C, B,S	120	90M	6.45 kg PVV-5A
	MON-50	T,C, B,S	60	50M	715g PVV-5A
YUGO	MRUD	C	60	50M	900g PE
ITALY	VS-DAFM 1	-	60	50M	-
CHINA	TYPE 66	T,C,P	60	50M	645g PE
UK	PAD	-	-	-	-
FRANCE	MAPED F1	C,B, P	60	40M	PE
GER	SM-70	T	-	-	110 gTNT

Fuzes - T=tripwire, C=command, B=breakwire, S=seismic, P=pressure

BOUNDING MINES

The first bounding AP mines were introduced by the Germans in 1935, and became known as the "S" mine.[17] When activated, a small propelling charge launched the mine to a height of 1 to 2 meters where it detonated. This type of mine has a lethal radius of between 15 and 30 meters, depending on the model. The three-pronged pressure fuzes (such as the US M605 or the Czech RO-8) commonly used with bounding AP mines have proven to be very resistant to explosive breaching techniques such as the MICLIC (Mine Clearing Line Charge) or the bangalore torpedo.[18] Currently, bounding AP mines similar to the US M16 "Bouncing Betty" or the Soviet OZM series are manufactured throughout the world (Table 7). One of the most advanced bounding AP mines is the US made ADAM (Area Denial Artillery Munition). The ADAM can be scattered by 155mm howitzers up to ranges of 17km, making it a particularly versatile scatterable mine. A modified version (the M86), may be hand emplaced as a "Pursuit Deterrent Munition (PDM)."[19]

Sophisticated add-on fuzes such as the Italian VS-APF1 for bounding AP mines are becoming available today. The VS-APF1 is an improved electronic fuze for the Valmara 69, which was encountered in large numbers during the Persian Gulf War. The VS-APF1 has a ten minute safe arming delay. After this delay, it dispenses three highly sensitive tripwires. This device also has a field programmable self-neutralization time, giving the user the option of having his minefield neutralize at a preprogrammed time. After the mines have self-neutralized, they can be recovered and reused.[20] This fuze allows the upgrade of "dumb" first generation in to modern self-neutralizing "smart" mines. Among the important concerns for the countermine designer is the early detection and neutralization of approach hazards (tripwires, breakwires, seismic sensors, and command detonation) and ballistic survivability.

TABLE 7: BOUNDING AP MINES

Origin	Mine	Fuze	Lethal Radius	Explosive
US	M16A2	T,C,P	30M	590 g TNT
	ADAM/PDM	T	6-10M	21 g Comp A5
USSR	OZM-3	T,C,B,S,P	25M	75 g TNT
	OZM-4	T,C,B,S,P	25M	170 g TNT
	OZM-72	T,C,B,S,P	25-30M	700 g TNT
CZECH	PP-Mi-Sr	T,C,P	20M	362 g TNT
	PP-Mi-Sr II	T,C,P	20M	362 g TNT
YUGO	PROM-1	T,P	22M	425 g TNT
ITALY	VALMARA 69	T,P	27M	576 g Comp B
	BM-85	T,P	20M	450 g Comp B
	P-40	T	22M	480 g TNT
	VS-SAPFM 3	T	25M	450g Comp B
CHINA	TYPE 69	T,P	13M	105 g TNT
FRANCE	M1951/1955	T,B,TR	45M	408 g Picric Acid
GER	DM-31	T	50M	530 g

Fuzes - T=tripwire, C=command, B=breakwire, S=seismic, P=pressure, TR=tilt rod

SIMPLE FRAGMENTING MINES

Stake-mounted fragmenting AP mines have been employed since World War II without significant change to their design.[21] Some of the better known examples include the Soviet made POMZ-2 and the Czech PP-Mi-Sk (Table 8).

Recently, several countries, including the US[22] and the former Soviet Union[23], have developed and fielded scatterable

fragmenting AP mines (Table 9) which employ advanced electronic fuzing. These are grouped in a separate table because of the critical employment differences between the two types. These scatterable mines are frequently emplaced during runway denial missions and to deny enemy access to his Nuclear, Biological and Chemical weapons storage facilities as was done during the Persian Gulf War.[24] Among the important concerns for the countermine designer is the early detection and neutralization of approach hazards (tripwires) and ballistic survivability.

TABLE 8: COMMON SIMPLE FRAGMENTING AP MINES

Origin	Mine	Fuze	Lethal Radius	Explosive
US	M-3	T,P	9 M	408 g TNT
USSR	POMZ-2M & POMZ-2	T	4 M	75 g TNT
CZECH	PP-Mi-Sk	T	4 M	75 g TNT
YUGO	PMR-2	T	-	100 g TNT
	PMR-3	T	8 M	410 g TNT
ITALY	P-25	T	10 M	180 g TNT or T4
CHINA	TYPE 58	T	4 M	75 g TNT
	TYPE 59	T	4 M	75 g TNT
FRANCE	M-63	T,P	-	30 g Tetryl
	M-61	T,P	-	57 g TNT

Fuzes - T=tripwire, P=pressure

TABLE 9: SCATTERABLE FRAGMENTING AP MINES

Origin	Mine	Fuze	Lethal Radius	Emplacement	Remarks
US	M-74	T	10-15M	H,F,V	SD: 4,48 HRS, 5,15 DAYS
USSR	POM-2	T	-	-	PTM-1 COMPANION
GER	AP-2	T	20M	H,V,R,M	AT-2 COMPANION

Fuzes - T=tripwire, Emplacement - H=helicopter, F=fixed wing aircraft, V=vehicle dispensed, R=Rocket, M=Manual, Remarks - SD=Self-Destruct

UNEXPLODED SUBMUNITIONS

There is one other threat which resembles a scatterable minefield that must be considered. The high dud rates of submunitions effectively create nuisance minefields in areas that have been bombed or shelled prior to a ground attack. The dud rate is increased in jungle, swamp or deep snow. These munitions can be delivered by tactical air strikes and artillery. Further complicating this problem is the fact that data on areas expected to contain large numbers of duds is not provided through fire support channels to maneuver units or their supporting engineers. This problem was vividly illustrated during Desert Storm where objectives and the areas immediately adjacent to them were found to be covered with submunitions to a surprisingly great degree.[25]

BLAST AP MINES

Blast AP mines are descended from the large underground mines that were dug under fortified positions and then detonated. Modern blast AP mines are produced by a number of countries (Table 10). Significant improvements have been made to "toe popper" mines, which, despite their inherent simplicity, have been used with devastating effectiveness over the years, most recently by the Soviets in Afghanistan. Examples include the PFM-1 and PMN. These improvements include virtual elimination of metal (to decrease detectability), blast over-pressure protection, low operating thresholds, integral

TABLE 10: COMMON BLAST AP MINES

Origin	Mine	Metal Content	Explosive	Emplacement
US	M-14*	LOW	29 g Tetryl	M
USSR	PMN-2	YES	115 g TNT	M
	PMN	YES	200 g TNT	M
	PFM-1	YES	40 g Liquid	F,H,Mo
	PMD-6M	YES	200 g TNT	M
CZECH	PP-Mi-Ba	LOW	200 g TNT	M
	PP-Mi-D	YES	200 g TNT	M
YUGO	UDAR	YES	20 kg FAE	M
	PMA-1	LOW	200 g TNT	M
	PMA-2	LOW	100 g TNT	M
	PMA-3	LOW	35 g TNT	M
ITALY	SB-33	.86 g	35 g	H,M
	VS-50	.86 g	43 g RDX	H,M
	VS-MK2	.86 g	33 g RDX	H,V,M
CHINA	TYPE 72	LOW	34 g TNT	M
UK	RANGER	YES	10 g RDX	V
FRANCE	M-59	LOW	57 g Tetryl	M
	M1951	LOW	51 g PETN	M
GER	PPM-2	LOW	110 g TNT	M
	DM-11	LOW	114 g RDX/TNT	M

Emplacement - H=helicopter, V=vehicle dispensed, Mo=mortar, M=manual
*The M14 has been withdrawn from US stockpiles.

antihandling devices, and self-destruct or self-neutralization options. Many of these are also suitable for scatterable mine laying. The most significant advances in blast AP mines can be found in Italian mines such as the SB-33 or the VS-Mk2. One of the most unusual blast AP mines is the Yugoslav UDAR, a command detonated bounding FAE (Fuel-Air Explosive) mine.[26] Among the important concerns for the countermine designer is the safe detection of low metallic content mines.

CHEMICAL MINES

The British developed Livens Projector was first employed in 1917 and is arguably the first chemical mine.[27] Except for the introduction of nerve agent fills, no significant improvements have occurred in the design of chemical mines since WWII. Only the US and the former Soviet Union have been identified as producing them (Table 11).[28] However, It should be noted that most blast AT mines can be readily converted to chemical mines by removing the main charge and replacing it with the desired chemical agent. Chemical mines are typically identifiable by their color or markings. These are intended to be integrated within normal minefields.[29] Flame mines such as the improvised flame fougasse occasionally employed by American engineers are also technically classified as chemical mines.

TABLE 11: CHEMICAL MINES

Origin	Nomenclature	Fuze	Fill	Remarks
US	M-1	C	H, HD	SCHEDULED FOR DESTRUCTION
	M-23	P,C	VX	SCHEDULED FOR DESTRUCTION
USSR	KHF-1/KHF-2	C	H	
CHINA	?	-	-	

Fuzes - P=pressure, C=command

BOOBYTRAPS

Boobytraps and Improvised Explosive Devices (IEDs) are an adjunct to AP mines and are frequently employed in an urban environment. They can utilize any of the kill mechanisms discussed earlier. The primary advances in boobytraps have come in the area of fuzing. Some examples include light sensitive devices (based on photovoltaic cells) that detonate when light of sufficient intensity strikes a sensor, and anti-probe pads that initiate the main charge if a soldier using a probe pushes against it.[30] However, these devices are rare. The vast majority of boobytraps the soldier can expect to encounter will be relatively simple but cunning devices that use mechanical or electro-mechanical firing devices.[31] Some of the most advanced boobytrap devices were manufactured in Yugoslavia. These are the "Superquick Family of Electronic Fuzes" and they have seven different activation options.[32]

III. MINE EMPLOYMENT

In order for the requirements writer, the battle simulator and the system designer to make informed decisions on the mine threat definition for a given system, it is necessary to understand how and where mines will be employed in different situations. From this, it is possible to determine rough probabilities of encounter against the different mine threats. These probabilities will be a function of the threat's mine inventory, doctrine and situation. These factors will evolve with time and must be periodically reconsidered, particularly in light of the availability of many advanced mines on the open market. Threat doctrine can be used to predict where mines will be encountered and in what manner (i.e. density, mix, emplacement techniques, etc.). This information should help decrease the probability of over/under design and limit the needless expenditure of lives and money.

Although no two minefields are exactly alike, there seems to exist three basic mine warfare doctrines in the world: US/NATO, Russia/former Warsaw Pact, and Guerilla (such as Viet Cong). The differences are described below. The first two doctrines are focussed on battlefield countermobility. Guerilla mining activity is focussed on interdiction and harassment, in effect, a cheap substitute for artillery. Mines are also used by guerillas to control refugee movement and to undermine the political stature of their opponents. Because of the significant differences in how mines are used in conventional operations and OOTW, they will be discussed separately.

CONVENTIONAL OPERATIONS

North Korea and Iraq are the two threats most frequently cited as the basis for the current US strategy requiring the capability to win two nearly simultaneous medium regional conflicts.[33] Both countries possess large mine inventories which would figure prominently in a war with either (Appendix C). North and South Korea have emplaced large numbers of mines between them along the DMZ (Demilitarized Zone)[34] and Iraq still retains a large inventory of mines.[35] Many former Warsaw Pact members and former client states of the USSR continue to employ Soviet doctrine (Figure 1).

Iraq dramatically demonstrated the proliferation of advanced mines during Operation Desert Storm, when they employed mines from nine different countries of origin.[36] Their diverse inventory of advanced mines provides an excellent example of what is available on the open market.[37] US forces involved in future conventional operations must be prepared to face a mine threat similar in scale and sophistication to that found during the Persian Gulf War.

Minefields laid for conventional operations are routinely part of a complex obstacle system that typically includes a mix a AT and AP mines, wire obstacles, antitank ditches, and restrictive terrain (Figure 2). These obstacles are normally covered by direct and indirect fire.

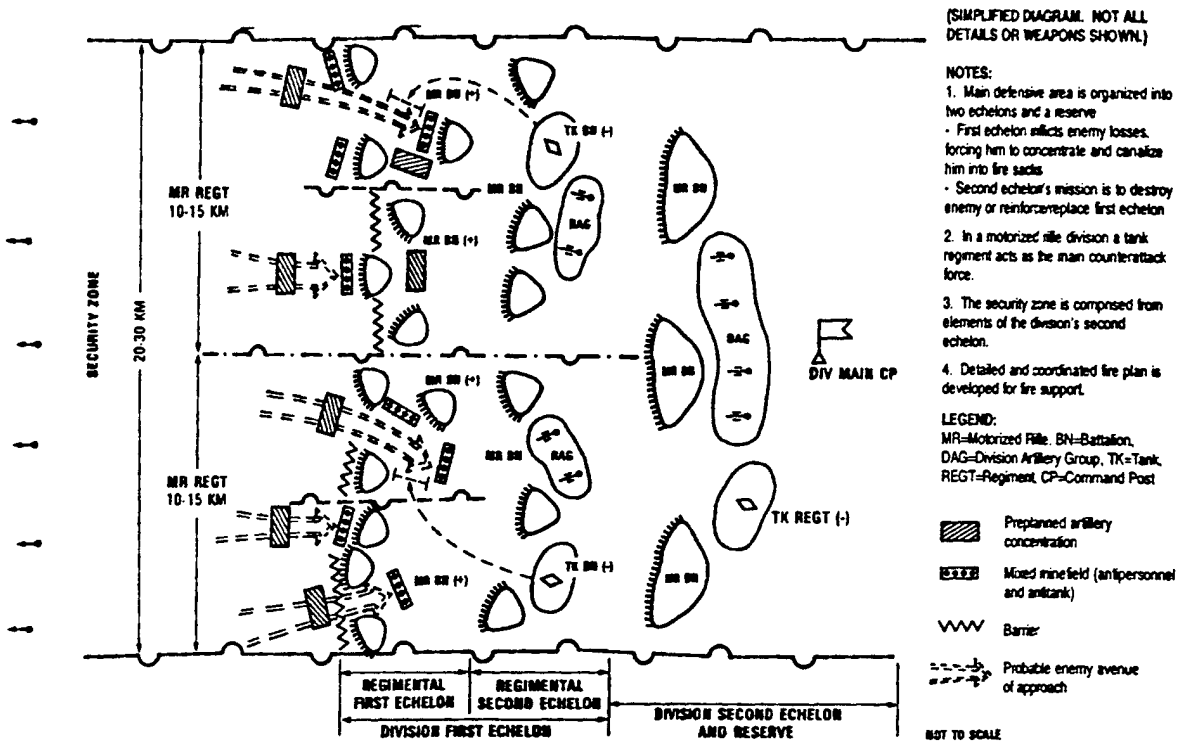


Figure 1: Schematic of doctrinal Soviet Defense

Minefield characteristics will also vary with their relative location in a dynamic battlefield environment. US/Allied situational obstacles consisting mostly of artillery/MRL (Multiple Rocket Launchers) and aircraft delivered scatterable mines can be placed well behind enemy front lines during deep battle operations. The main battle area should see the extensive employment of organic mine emplacement capability (manual, vehicle dispensers, and tube artillery) by either side. While US rear areas may see the emplacement of nuisance mining of LOCs (Lines of Communication) by enemy scatterable mines, special forces and/or guerrillas[38] as well as their own protective minefields around key installations. As the battlefield shifts, rear area units will also encounter the remains of obstacles in the old deep and main battle areas (such as breached/marked minefields, bypassed/unmarked minefields, and dud submunitions).

CONVENTIONAL MINEFIELD CHARACTERISTICS

MANUALLY EMPLACED MINEFIELDS

Although the characteristics of scatterable minefields are mainly a function of the delivery system, the doctrine for manually emplaced minefields differs between the US/NATO and Russia/Former Warsaw Pact. Considering that most third world militaries have been trained by one of these two parties, most conventional minefields encountered will be based on one of these two systems. For example, the Iraqi minefields used NATO type mine clusters with a mix of AT and AP mines, while the North Koreans employ Russian patterns with slight variations on mine spacing.

Among advanced nations, the employment of manually emplaced minefields by conventional militaries is expected to continue to decrease in favor of the use of scatterable mines. However, they will remain a significant presence on the battlefield for the foreseeable future. These minefields can be laid by the unit on the spot from resources at hand, in a manner that can be specially tailored to the situation.[39] The characteristics of these will vary with doctrine (Figures 3 & 4), time, equipment, training, available mines (Table 12 provides information on the probability of encountering different mine types in a manually emplaced minefield), and the situation. They are either tactical/protective nature or are employed as a nuisance. Manually emplaced tactical minefields will appear more frequently when the operational tempo slows and later in war, after the depletion of high tech mine stocks. The automatic self destruct/self neutralization features of advanced mines will prevent their use in barrier minefields (like those around Guantanamo Bay, the Korean DMZ, the Iraqi minefields placed in Kuwait, and along the old Inter-German border) that require an indefinite service life. Also obsolete, second generation mine laying systems such as GEMSS (Ground Emplaced Mine

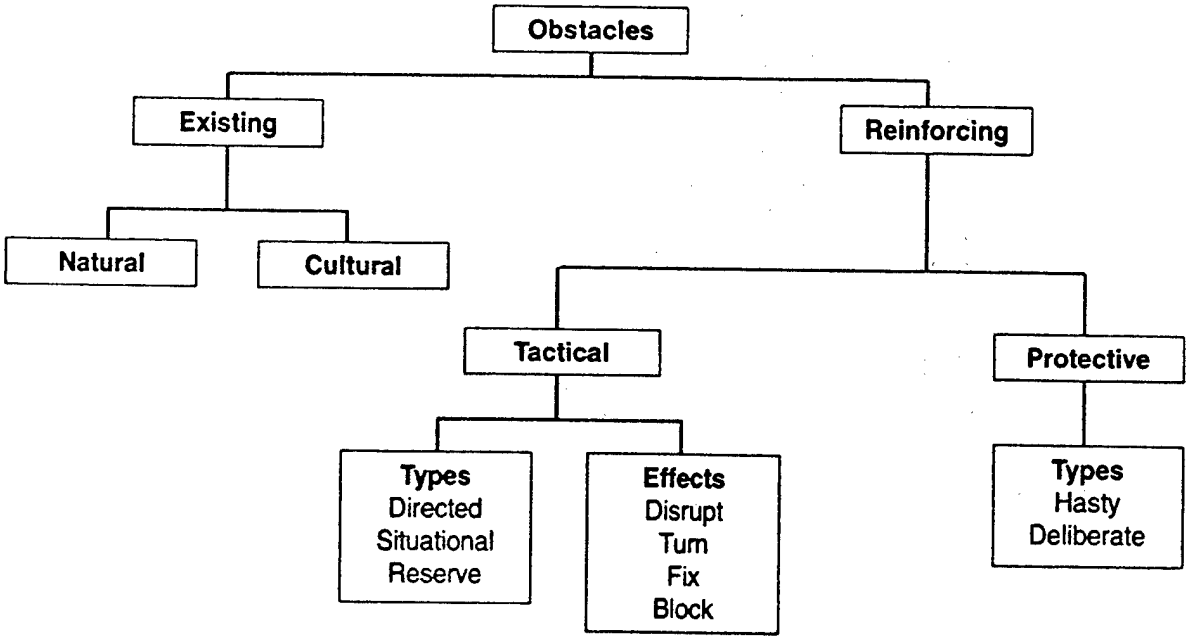


Figure 2: Obstacle types[40]

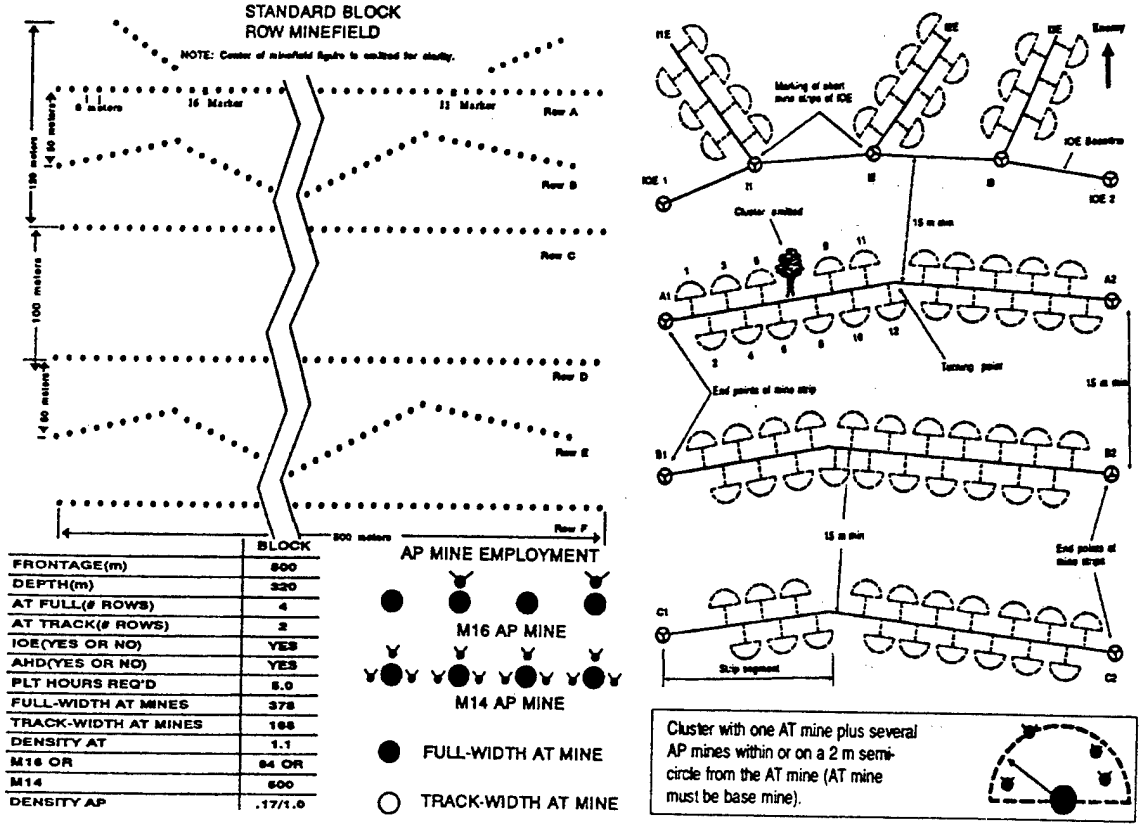


Figure 3: Manually Emplaced NATO Tactical Minefields

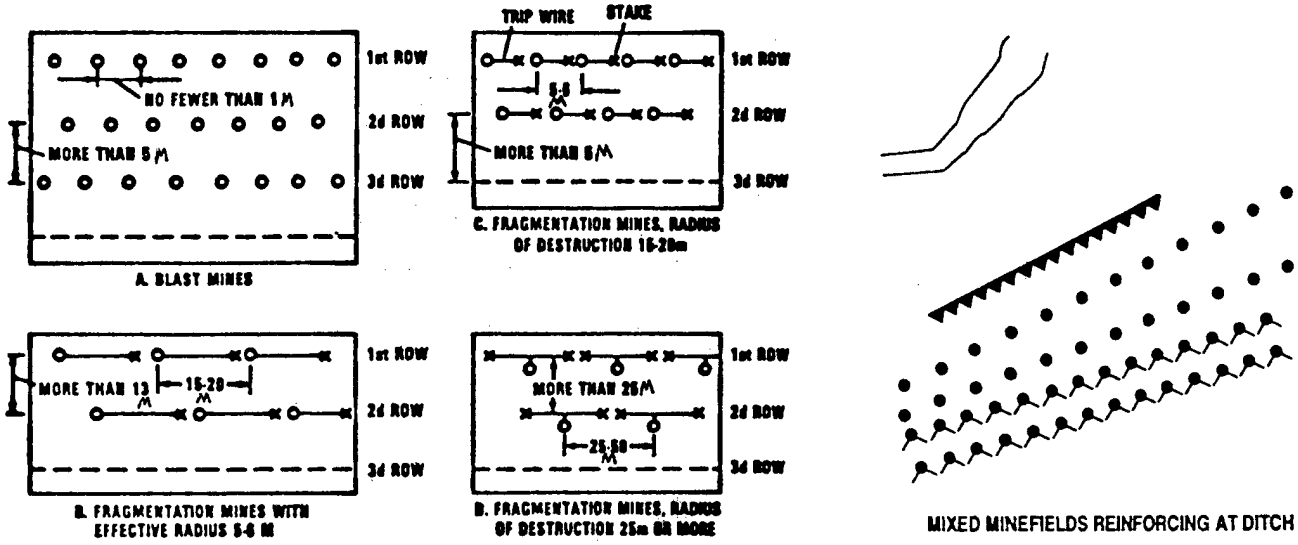


Figure 4: Manually Emplaced Russian Tactical Minefields

TABLE 12: MANUALLY EMPLACED MINEFIELDS*

	PRESENT						FUTURE**	
	RUSSIA	IRAQ	N KOREA	BOSNIA	US	NATO	RUSSIA	US
BLAST	1	1	1	1	-	-	1	-
DIRECTIONAL	1	4	-	1	1	2	1	1
BOUNDING	1	1	2	1	1	1	1	-
STAKE	1	4	1	1	-	4	1	-

Scored from 1 (most common) to 4 (very rare)
*This table is based on educated guesses and provides only very rough approximations.
**Through about 2005

TABLE 13: AP MINE EMPLACEMENT SYSTEMS

	Russia	China	Italy	Sweden	France	UK	US	Germany
Manportable Dispenser			X				X	
Vehicle Mounted Dispenser	X		X		X	X	X	X
Tube Artillery					X		X	
Multiple Rocket Launcher	X	X	X		F	F	F	X
Helicopter Delivered	X		X				X	F
Fixed Wing Aircraft Delivered	X					X	X	X

X-Current Capability, F-Future capability

Scattering System), the M-56 helicopter dispenser, and the M-57 towed mine planter may have to be employed in a long war, if they are still available. Manually emplaced minefields are generally located within direct fire range of defensive positions, although covering forces units may also employ them as part of their deception operations.[41]

MINE EMPLACEMENT SYSTEMS

Many countries possess a variety of mine emplacement systems (Table 13). The availability of these systems will significantly increase the influence of mines on the battlefield.

SCATTERABLE MINEFIELDS

Scatterable mines were first introduced by the Italians and Germans early in WW II. Since then, a wide variety of means have been developed to emplace them. Frequently, the mines employed by these systems are of the most advanced type (Tables 14 through 16 provide information on the probability of encountering different mine types in a variety of scatterable minefields). Many of the minefields emplaced by these delivery systems cover large areas (Figures 5 & 6) in a very short time. Additionally, these systems allow units to rapidly emplace considerably more mines than they could using just traditional manual methods (Table 19).

TABLE 14: VEHICLE EMPLACED MINEFIELDS*

	PRESENT						FUTURE**	
	RUSSIA	IRAQ	N KOREA	BOSNIA	US	NATO	RUSSIA	US
BLAST	-	-	-	-	-	2	-	-
DIRECTIONAL	-	-	-	-	-	-	-	-
BOUNDING	-	-	-	-	-	-	-	-
SIMPLE FRAG	1	-	-	-	1	1	1	1

Scored from 1 (most common) to 4 (very rare)
*This table is based on educated guesses and provides only very rough approximations.
**Through about 2005

TABLE 15: ARTILLERY/MRL EMPLACED MINEFIELDS*

	PRESENT						FUTURE**	
	RUSSIA	IRAQ	N KOREA	BOSNIA	US	NATO	RUSSIA	US
BLAST	-	-	-	-	-	-	-	-
DIRECTIONAL	-	-	-	-	-	-	-	-
BOUNDING	-	-	-	-	1	2	-	1
SIMPLE FRAG	1	-	-	-	1	1	1	1

Scored from 1 (most common) to 4 (very rare)
*This table is based on educated guesses and provides only very rough approximations.
**Through about 2005

TABLE 16: HELICOPTER/FIXED WING AIRCRAFT EMPLACED MINEFIELDS*

	PRESENT						FUTURE**	
	RUSSIA	IRAQ	N KOREA	BOSNIA	US	NATO	RUSSIA	US
BLAST	1	1	-	-	-	3	1	-
DIRECTIONAL	-	-	-	-	-	-	-	-
BOUNDING	-	-	-	-	-	-	-	-
SIMPLE FRAG	1	-	-	-	1	1	1	1

Scored from 1 (most common) to 4 (very rare)
*This table is based on educated guesses and provides only very rough approximations.
**Through about 2005

Expected minefield densities (Table 17) vary from .2 to 2.17 mines per meter of front, with an average of about .8 mines per meter of front. For a historical perspective, see Table 18 for the minefield densities found during some critical battles.

IV. OPERATIONS OTHER THAN WAR (OOTW)[42]

Since World War II, 70% of US personnel casualties in combat have occurred in OOTW.[43] In these conflicts, mines have also accounted for about 33% of our personnel losses. Most of the mines are emplaced in a manner similar to that used by the Viet Cong against the US during the Vietnam War. This guerilla "doctrine[44]" was been heavily exported by the old Communist block with examples of translated manuals turning up in Africa, Asia, and Central/South America. Mines can be emplaced with minimal risk by the guerrilla, while achieving significant disruptions to military operations and the civilian economy. The mine has become the guerrillas' weapon of choice.[45] They provide the guerrilla with an ideal "economy of force" capability and serve as an "equalizer" against a more technologically sophisticated opponent. It is expected that mines will continue to rank at the top of the guerrilla's list of preferred weapons. 400 to 600 million mines have been emplaced in the last 55 years of which 85 to 200 million remain active throughout the world.[46] These will constitute a serious threat to any US forces committed in these areas (Appendix D).[47] Military forces responding to peace keeping or humanitarian missions require great mobility. Keeping the region's lines of communication and economic infrastructure free from danger are

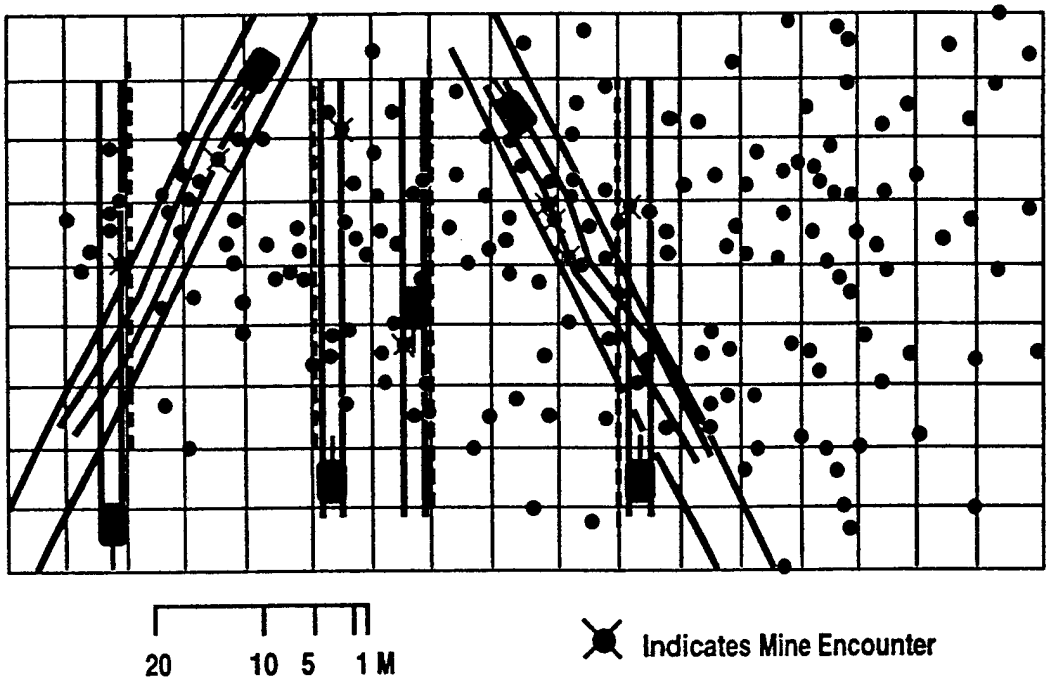


Figure 5: DAT minefield[48]

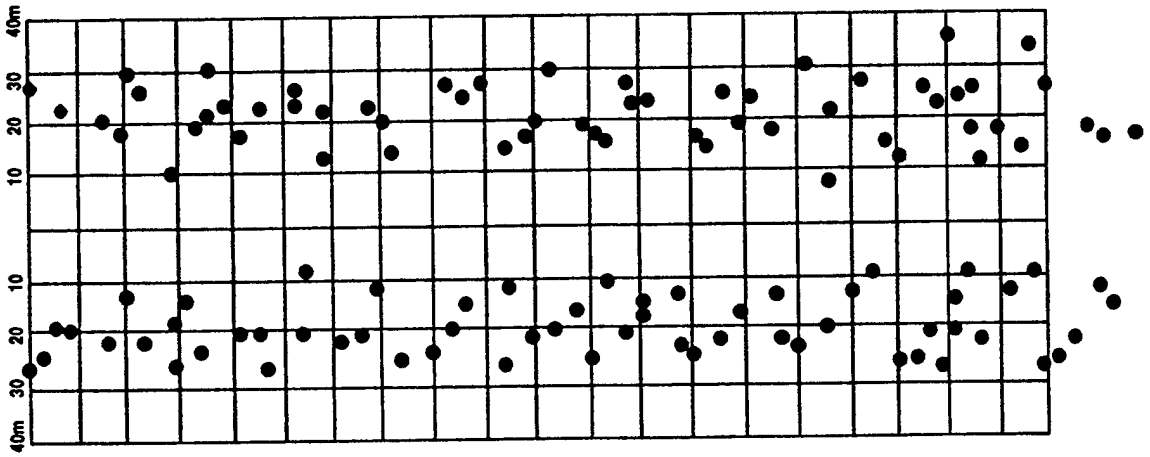


Figure 6: Skorpion minefield[49]

TABLE 17: MINE DELIVERY SYSTEMS[50]

Origin	System	Emplace*	Range	AP Mine Payload	Density**	Minefield Size
RUSSIA	BM-21	R	20km	POM-2	-	1000 X 500m per battery
	BM-22	R	35km	POM-2	-	Covers a large area rapidly
	PKPI	F,H	N/A	PFM-1, POM-2	-	Lays relatively narrow strips
	KGMU	F	N/A	PFM-1, POM-2	-	
	UMZ	V	N/A	POM-2	-	
ITALY	FIROS 25	R	22km	VS-Mk 2 EL, VS-SAPFM 3	-	1000 X 500m per battery
	FIROS 30	R	35km	VS-Mk 2 EL, VS-SAPFM 3	-	Covers large area rapidly
	DAT[51]	H	N/A	VS-Mk 2 EL, VS-SAPFM 3	-	Lays relatively narrow strips[52]
	Istrice	V	N/A	VS-Mk 2 EL, VS-SAPFM 3	-	Typically 360 X 140m
	Grillo 90	MD	N/A	VS-Mk 2 EL,	-	15 mines per dispenser
FRANCE	Minotaur[53]	V	N/A	In development	-	1200m X 600m
	EBG	V	N/A	In development	-	60 X 600m[54]
	155mm How	A	18 km	In development	-	8 mines per round[55]
UK	JP-233	F	N/A	HB 876	-	430 mines per Tornado aircraft[56]
	Ranger	V	N/A	L10	-	1296 mines per dispenser
GERMANY	Skorpion[57]	V,H	N/A	AP-2	-	1500 X 50m of 600 mines
	MW-1[58]	F	N/A	MUSPA	-	55-500m wide & 200-2500m long
	LARS[59]	R	14 km	AP-2	-	Footprint is probably similar to that of the BM-21.
	MARS[60]	R	30 km	AP-2	-	1000m
US	Gator	F	N/A	BLU-92/B	.66[61] or .2	132 AP mines in an area Approx. 200 X 650m per aircraft
	Volcano	V,H	N/A	BLU-92/B	.14	Two 1,110 m strips, 35m deep with 70m (air delivered) or 50m(ground dispensed) between strips, 960 mines capacity[62]
	155mm How	A	17km	ADAM	.1 to .8	Emplaced in modules 400 X 400m or 200 X 200m
	M-56	H	N/A		1.6	100m X 40m with 160 M-34 ATmines[63]
	M-128 GEMMS	V	N/A	M74	.2	1000 X 280 to 380m deep[64]
	M-131 MOPMS	MD	N/A	M132	.06	4 AP mines in a 35 m radius semi-circle.

* A=artillery, H=helicopter, F=fixed wing aircraft, R=rocket, V=vehicle dispensed, MD=manportable dispenser
**In mines per meter of front

TABLE 18: HISTORICAL MINE DENSITIES

BATTLE	DATE	MINES PER KM OF FRONT[65]
EL ALAMEIN	OCT/NOV 1942	7,000[66]
KURSK	JUL 1943	2,400[67]
D-DAY (Omaha Beach)	JUN 1944	1,300[68]
GULF WAR	FEB 1991	2,000[69]

critical components for successfully resolving the problem.

Mine employment by guerrillas typically consists of random nuisance mining along lines of communications (often as part of an ambush) as well as protective minefields around base camp areas, and denial mining of villages and agricultural areas.[70] The primary threat to personnel is from blast AP mines.

V. COUNTERMINE

The availability of countermine equipment in many situations will reduce the probability of encounter through detection (avoidance)/neutralization and should be considered for determining probability of encounter. Although the US has fielded some countermine equipment in the last ten years,[71] US countermine capabilities and tactics across the board are still significantly less than 100% effective.[72] US personnel are vulnerable to the mines that these systems will "miss."[73] As MG

TABLE 19: DAILY DIVISIONAL OBSTACLE EMPLACEMENT CAPACITY[74]

	RUSSIA		US	
OBSTACLE TYPE	ASSETS	LINEAR OUTPUT	ASSETS	LINEAR OUTPUT
Manual MF (Protective)	All Cbt Units	2.2 km[75]	All Cbt Units	14.7 km
(Tactical)	5 Engr Plt	9.3 km	27 Engr Plt	75.0 km[76]
Mechanical MF*	GMZ X 3[77]	2.4 km	Volcano X 6	6.6 km[78]
	UMZ X 4	1.0 km		
	PMZ-4 X 8	6.4 km[79]		
Artillery MF*	BM-21 X 18	6.0 km	M-109 X 72	23.0 km[80]
Helicopter MF*	PKPI (Mi-24 X 6)		Volcano X 3	3.3 km
	VMR-2 (Mi-8 X 4)	2.1 km[81]		
Fixed Wing MF	N/A		N/A[82]	
TOTAL MINEFIELDS		31.6 km		122.6 km
ANTITANK DITCHES	MDK-3 X 6	10.1 km	M-9 ACE X 63	16.2 km
TOTAL OBSTACLES		41.7 km		138.8 km

* These capabilities are frequently held in reserve to provide rapid situational obstacle emplacement
MF-minefield

Gill, Commandant, US Army Engineer School asked, "Why does something have to get broken (I mean really broken, like countermine) before we focus attention and rally resources?"

Furthermore, the US Army remains poorly equipped and trained to deal with mines in a low intensity conflict scenario. The capabilities of US light forces have not significantly changed since the Vietnam War.[83] In fact, US dismounted soldiers are using essentially the same technology that was available during World War II.[84] This is because countermine equipment was a low priority during the Cold War when the US was preparing to fight a defensive battle in Central Europe.

The technical advances in AP mines have significant operational and tactical implications for future US combat operations.[85] Currently, in the never ending spiral of measure/counter-measure/counter-counter-measure, the mines are well ahead. Countermine equipment is increasingly inadequate to deal with the threat, both in terms of capability and quantity. For this reason, it is necessary to carefully consider the mine threat during system design/selection.

VI. DEMINING

Some of the earliest examples of area mine clearance occurred during the American Civil War when irate Union soldiers under the commands of Generals McClelland and Sherman forced Confederate POWs to clear mines ("land torpedoes") around Williamsburg, Virginia and Ft McAllister, Georgia. Some emplaced Confederate landmines have been found as recently as 1960 near Mobile, Alabama.[86]

The first post-conflict demining operations were conducted in France following World War I. At this time, US engineers cleared thousands of German land mines. The 108th Engineer Regiment, 33rd Infantry Division alone cleared over 6,000.[87] After World War II, an estimated 45,000 man-days were required to clear 8 million mines from France, Germany and Belgium alone.[88] The British had cleared 280,000 of their mines from their beaches by March, 1946. This work continued through at least 1958.[89] In the last twenty years, significant demining operations have been performed along the Suez Canal, Afghanistan, Kuwait, Cambodia, Somalia, El Salvador, Angola, Somalia, and Bosnia to name just a few. Emerging US doctrine is contained in TC 31-34 Demining Operations (Initial Draft).[90]

VI. CONCLUSIONS

Mines directly attack the basis of current US doctrine by limiting tactical maneuverability and slowing operational tempo, yet the US has fielded very little to counter this threat. If US forces are to accomplish their assigned missions with minimal casualties, it is essential that mines be recognized for the threat that they represent. US military systems must be designed accordingly, since mines typically account for a significant portion of our casualties in both conventional operations and OOTW.

Many nations have developed and are exporting scatterable mines that can be placed throughout the whole area of operations even deep in US rear areas where logistic units are not supported with any significant countermine capability.[91] One thing is certain: US deficiencies in countermine threatens the mobility necessary to successfully execute current doctrine, possibly jeopardizing the successful completion of many combat operations and OOTW.

TABLE A-1: US ARMY MINE CASUALTY SUMMARY[a]

	TANKS		PERSONNEL					
			KILLED IN ACTION[b]		WOUNDED IN ACTION[c]		TOTAL CASUALTIES	
(1) THEATER OF OPERATIONS	(2) ESTIMATED TOTAL LOSSES TO ENEMY CAUSES[d]	(3) ESTIMATED TOTAL MINE LOSSES[e]	(4) ESTIMATED TOTAL KIAs TO ENEMY CAUSES	(5) ESTIMATED TOTAL MINE KIAs	(6) ESTIMATED TOTAL WIAs TO ENEMY CAUSES	(7) ESTIMATED TOTAL MINE WIAs	(8) ESTIMATED TOTAL LOSSES TO ENEMY CAUSES[aa]	(9) ESTIMATED TOTAL MINE CASUALTIES[bb]
WORLD WAR I	(38)	(6) (16%)	-	-	-	-	-	-
WORLD WAR II (OVERALL)	4,936	1,142 (23%)	169,384	4,653 (2.7%)	507,873	25,529 (5.1%)	674,382	30,182 (4.5%)
MEDITERRANEAN	840	243 (29%)	32,756	1,510 (4.6%)	91,223	5,366 (5.9%)	123,979	6,876 (5.5%)
WESTERN EUROPE	3,741	783 (21%)	108,926	2,604 (2.4%)	334,889	15,759 (4.7%)	443,815	18,363 (4.1%)
PACIFIC	355	116 (33%)	27,702	539 (1.9%)	78,886	1,529 (1.9%)	106,588	2,068 (1.9%)

[a] ( ) indicates partial data set, if not a percentage. Due to round-off errors and the fact that some of the data is incomplete, the numbers may not exactly add-up.

[b] Data taken from Table A-2, column (6).

[c] Data taken from Table A-6, columns (3) & (7).

[d] WWII Data taken from Table A-5, column (2) minus column (4).

[e] Data taken from Table A-5, columns (6) & (7).

[aa] Column (4) plus column (6)

[bb] Column (5) plus column (7), percentage calculated by dividing column (9) by column (8)

TABLE A-1: US ARMY MINE CASUALTY SUMMARY (CONTINUED)

	TANKS		PERSONNEL					
			KILLED IN ACTION		WOUNDED IN ACTION		TOTAL CASUALTIES	
(1) THEATER OF OPERATIONS	(2) ESTIMATED TOTAL LOSSES TO ENEMY CAUSES	(3) ESTIMATED TOTAL MINE LOSSES	(4) ESTIMATED TOTAL KIAs TO ENEMY CAUSES	(5) ESTIMATED TOTAL MINE KIAs	(6) ESTIMATED TOTAL WIAs TO ENEMY CAUSES	(7) ESTIMATED TOTAL MINE WIAs	(8) ESTIMATED TOTAL LOSSES TO ENEMY CAUSES	(9) ESTIMATED TOTAL MINE CASUALTIES
KOREA	-	- (56%)	17,488	779 (4.5%)	65,170	2,451 (3.8%)	82,658	3,230 (3.9%)
VIETNAM	(116)	(85) (73%)	26,480	7,318 (28%)	167,771	56,783 (34%)	194,251	64,101 (33%)
PERSIAN GULF	10[a]	**6 (60%)**	136	46 (34%)	467	(14) (3.0%)	603	(60) (10%)
SOMALIA	11	6 (55%)	28	7 (25%)	137	(9) (6.6%)	165	(16) (9.7%)
BOSNIA	6	6 (100%)	1	1 (100%)	4	4 (100%)	5	5 (100%)
TOTAL[b]	5,117[c]	1,251 (24%)	213,517	12,811 (6.0%)	740,883	84,790 (11%)	954,939	97,594 (10%)

[a] Includes USMC casualties

[b] The following are not included in these totals, Grenada: 19 dead, 119 wounded, Beirut: 241 dead, 79 wounded, Panama: 23 dead, 320 wounded.

[c] Tank chassis based vehicles only, does not include APCs/IFVs or other tactical vehicles.

TABLE A-2: US ARMY GROUND PERSONNEL MINE KIAs (WORLD WAR II TO PRESENT)

(1) THEATER OF OPERATIONS	(2) TOTAL KIAs[a]	(3) ESTIMATED GROUND KIAs TO ENEMY CAUSES[a]	(4) ESTIMATED TOTAL TANK CREW KIAs[b]	(5) ADJUSTED TOTAL GROUND KIAs TO ENEMY CAUSES[c]	(6) TOTAL ESTIMATED MINE KIAs[d]
WWII (OVERALL)[e]	192,220	165,046	4,338	169,384	4,653
MEDITERRANEAN	35,185	32,018	738	32,756	1,510
WESTERN EUROPE	120,043	105,638	3,288	108,926	2,604
PACIFIC	31,787	27,390	312	27,702	539[aa]
KOREA	17,488	17,488	-	17,488	779
VIETNAM	30,904	26,480	-	26,480	7,318
PERSIAN GULF[bb]	148	135	1	136	46
SOMALIA	31	28	0	28	7
BOSNIA	1	1	0	1	1

[a] Data taken from Tables A-3 & A-4, rows labeled Total KIA and Total Estimated Ground KIAs.

[b] Column (8), Table A-5 plus Total Estimated Ground KIAs Row (Tables A-3 and A-4).

[c] Column (3) plus column (4).

[d] Column (9), Table A-5 plus Total Estimated Mine KIAs Row (Tables A-3 and A-4).

[e] The WWII (Overall) Total KIAs are greater than the sum of the theaters shown, because it appears to include minor theaters of operation such as CBI (China-Burma-India).

[aa] The Japanese lacked effective antipersonnel mines throughout the war. They only began to employ AT mines effectively late in the war during the campaigns in the Phillippines, Iwo Jima and Okinawa.

[bb] Includes USMC casualties

TABLE A-3: US ARMY CASUALTIES KILLED IN ACTION IN WORLD WAR II, BY MUNITION[a]

	(1) WESTERN EUROPE	(2) MEDITERRANEAN	(3) SOUTHWEST PACIFIC	(4) PACIFIC OCEAN AREA	(5) OVERALL PACIFIC[b]	(6) TOTAL KIAs[c]
TOTAL KILLED IN ACTION	120,043	35,185	19,426	12,361	31,787	192,220[d]
KILLED BY KNOWN MUNITION	53,553	18,809	11,940	4,278	16,218	90,975[d]
BOMBS	536 (1%)	376 (2%)	239 (2%)	86 (2%)	325 (2%)	1,237 (1%)
SHELLS	26,777 (50%)	12,226 (65%)	3,343 (28%)	1,711 (40%)	5,054 (31%)	44,057 (50%)
BULLETS	17,137 (32%)	3,762 (20%)	6,209 (52%)	1,882 (44%)	8,091 (50%)	28,990 (32%)
MINES[e]	1,071 (2%)	752 (4%)	239 (2%)	43 (1%)	282 (2%)	2,105 (2%)
GRENADES	-	-	119 (1%)	43 (1%)	162 (1%)	162 (0.1%)
TOTAL GROUND KIAs	45,521 (88%)	17,116 (91%)	10,149 (85%)	3,765 (89%)	13,914 (86%)	76,551 (85%)
TOTAL ESTIMATED GROUND KIAs	105,638	32,018	16,512	10,878	27,390	165,046
TOTAL ESTIMATED MINE KIAs	2,430 (2.3%)	1,460 (4.4%)	389 (2.4%)	124 (1.1%)	513 (1.9%)	4,403 (2.7%)[aa]

[a] Data taken from Conventional Warfare, Ballisitc, Blast, and Burn Injuries, Table 2-8, page 62, percentages are given in reference to Total Ground KIAs.

[b] Column (3) plus Column (4).

[c] The sum of Columns (1), (2), & (5).

[d] The Total KIAs and Killed by Known Munition rows are greater then the sum of columns (1), (2), & (5) because they appear to include minor theaters of operation such as CBI (China-Burma-India).

[e] Considering that the initial data was rounded off to the nearest percentage point, the accuracy of the mine casualty figures is limited to ± 25%.

[aa] This is consistent with Warfare and Armed Conflicts, A statistical Reference, Volume II, by Michael Clodfelter, McFarland and Company, 1992, page 959, which gave an overall estimate of 2.7% KIA by mines plus 0.2% KIA by boobytraps.

TABLE A-4: US ARMY CASUALTIES KILLED IN ACTION SINCE WORLD WAR II, BY MUNITION

	KOREA[a]	VIETNAM[b]	PERSIAN GULF[c]	SOMALIA[d]	BOSNIA[e]	TOTAL[aa]
TOTAL KIA	17,488	30,904	148	31	1	48,572
KILLED BY KNOWN MUNITION	6,845	26,259	75	28	1	33,208
SHELLS	3,859 (56%)	2,399 (9.1%)	42 (48%)	1 (3.4%)	-	6,301
BULLETS	2,584 (38%)	12,389 (47%)	4 (4.5%)	20 (69%)	-	14,997
MINES	305 (4.5%)	7,246 (28%)	29 (33%)[bb]	7 (27%)	1 (100%)	7,588
GRENADES	97 (1.4%)	4,225 (16%)	-	-	-	4,322
OTHER	-	-	13	3	-	16
UNKNOWN	10,643	258	53	-	-	10,954
TOTAL ESTIMATED GROUND KIAs	17,488	26,480	135	28	1	44,132
TOTAL ESTIMATED MINE KIAs	779 (4.5%)	7,318 (28%)	46 (33%)	7 (25%)	1 (100%)	8,151

[a] Data taken from Conventional Warfare, Ballisitc, Blast, and Burn Injuries, Table 2-11, page 64.

[b] U.S. CASUALTIES IN SOUTHEAST ASIA, Statistics as of November 11, 1986, Washington Headquarters Services, Directorate for Information, Operations and Reports, U.S. Department of Defense, page 10. See the discussion in this appendix for the method used to estimate the breakout of US casualties in Vietnam. Based on Table 2-15 (page 66) in Assessing the Effectiveness of Conventional Weapons, AP mines and boobytraps accounted for 71% of the mine KIAs and 56% of the WIAs. See also the discussion at the end of this Appendix.

[c] Desert Warriors, The Men and Women Who Won the Gulf War, by the staff of USA Today, May 1991, pages 99-206 and Desert Shield/ Desert Storm, Army Times After Action Reports, 1991-1992. Including 32 friendly fire KIAs to shells and 3 friendly Fire KIAs to small arms.

[d] Includes 2 DA civilian and USMC and casualties. See "After Action Report, Operation Restore Hope," by William C. Schneck, Belvoir RD&E Center, Ft Belvoir, VA, 1994, Appendices B & D, and "Quick Reaction Force, Falcon Brigade, 10th Mountain Division, Summary of Combat Operations on 3 October 1993," by COL Lawrence Casper, 10th Aviation Brigade, Mogadishu, Somalia, undated.

[e] "Task Force Eagle Mine Strike Summary," as of 5 August 1996. Based on "Development and Test of an Antitank Mine Blast System for Crew Compartment Protection in the HMMWV," by Charles Williams and Thompson Richmond, Proceedings of the Sixth Annual TARDEC Combat Vehicle Survivability Symposium (U), May 1995, page 129, Table 1, AP mines have accounted for 33% of the Canadian mine casualties in Bosnia. AP mines are responsible for the one American killed and two of the four wounded.

[aa] The following are not included in these totals, Grenada: 19 dead, Panama: 23 dead.

[bb] Includes 17 KIA by UXO (unexploded ordnance). These are included as mine casualties because UXOs are classified as mines according to JP 1-02 which states "Mine - In land mine warfare, an explosive or other material normally encased, designed to destroy or damage ground vehicles, boats, or aircraft, or designed to wound, kill, or otherwise incapacitate personnel. It may be detonated by the action of its victim, by the passage of time, or by controlled means."

TABLE A-5: US AND ALLIED TANK CASUALTIES WWI TO PRESENT[a]

(1) THEATER OF OPERATIONS	(2) TOTAL TANKS LOSSES	(3) KNOWN CAUSE TANKS LOSSES	(4) KNOWN NON-ENEMY LOSSES	(5) KNOWN TANK LOSSES TO MINES	(6) PERCENT TANK LOSSES TO MINES[b]	(7) ESTIMATED TANK LOSSES TO MINES[c]	(8) ESTIMATED US CREW CASUALTIES KIA/WIA[d]	(9) ESTIMATED CREW MINE CASUALTIES KIA/WIA[e]
WESTERN EUROPE TOTAL	6,787	5,691	720	1,107	22.2%	1,351	-	-
US	4,257	3,448	516	614	20.9%	783	3,288/6,251	174/604
ALLIED (UK, CANADA)	2,530	2,243	204	493	24.2%	562	-	-
NORTH AFRICA TOTAL	2,034	1,875	27	288	15.6%	313	-	-
US	277	118	26	19	20.7%	52	221/419	12/40
ALLIED (UK, FRANCE)	1,757	1,757	1	269	15.3%	269	-	-
SICILY TOTAL	109	72	8	18	28.1%	28	-	-
US	58	21	4	2	11.8%	6	47/90	1/5
ALLIED (UK, CANADA)	51	51	4	16	34.0%	16	-	-
ITALY TOTAL	2,299	1,883	447	412	28.7%	531	-	-
US	685	588	150	137	31.3%	167	470/894	37/129
ALLIED (UK, CANADA)	1,614	1,295	297	275	27.6%	363	-	-
MEDITERRANEAN TOTAL[aa]	4,442	3,830	482	718	21.4%	847	-	-
US	1,020	727	180	158	28.8%	243	738/1403	50/174
ALLIED (UK, CAN, FR)	3,422	3,103	302	560	20.0%	624	-	-

[a] Survey of Allied Tank Casualties in World War II, by Alvin Coox and L. Van Loan Naisawald, ORO-T-117, Research Office, The Johns Hopkins University, Ft McNair, Washington, D.C., 31 March 1951, Table 11.

[b] Column (5) divided by the quantity of column (3) minus column (4).

[c] Column (6) times the quantity of column (2) minus column (4).

[d] Based on Survey of Allied Tank Casualties in World War II, Table XXII, page 40, assumes .0466 KIA and .1832 WIA per tank lost times column (2) minus column (4).

[e] Based on Survey of Allied Tank Casualties in World War II, Table XXII, page 40, assumes .2223 KIA and .7714 WIA per tank lost to a mine.

[aa] The Mediterranean Theater is the sum of North Africa, Sicily, and Italy.

TABLE A-5: US AND ALLIED TANK CASUALTIES WWI TO PRESENT (CONTINUATION)

(1) THEATER OF OPERATIONS	(2) TOTAL TANKS LOSSES	(3) KNOWN CAUSE TANKS LOSSES	(4) KNOWN NON-ENEMY LOSSES	(5) KNOWN TANK LOSSES TO MINES	(6) PERCENT TANK LOSSES TO MINES	(7) ESTIMATED TANK LOSSES TO MINES	(8) ESTIMATED US CREW CASUALTIES KIA/WIA	(9) ESTIMATED CREW MINE CASUALTIES KIA/WIA
PACIFIC TOTAL	809	772	137	214	33.7%	227	591/1,123	51/175
US ARMY	393	384	38	113	32.7%	116	312/593	26/89
USMC	416	388	99	101	34.7%	111	279/530	25/86
ALL THEATERS TOTAL[a]	12,140	10,388	1,339	2,058	22.7%	2,456	-	-
US ARMY	5,670	4,559	734	885	23.1%	1,142	4,338/8,247	250/867
ALLIED (UK, CAN, FR, USMC)[a]	6,470	5,829	605	1,183	22.6%	1,328	-	-
KOREA[b]	-	-	-	-	56%	-	-	-
VIETNAM[c]	-	(116)	-	(85)	73%	-	-	-
PERSIAN GULF[d]	10	10	-	6	60%	-	-	-
SOMALIA[e]	11	11	-	6	55%	-	-	-
BOSNIA[aa]	6	6	-	6	100%	-	-	-

[a] Includes British losses in Burma which are not shown elsewhere in the Table.

[b] Countermine Systems Directorate Briefing. It reached as high as 70% during offensive operations. See FM 20-32, September 1976, page 135.

[c] "Mine Warfare in Vietnam," The Mine Warfare Center, Engineer Section, Headquarters, United States Army Vietnam, August 1969, incl. 8.

[d] Includes USMC casualties. Two M-1s of the 5 lost were disabled by mines, see From Shield to Storm, by James F. Dunnigan and Austin Bay, William Morrow & Co., New York, New York, 1992, pages 294-295. 4 USMC M-60s were knocked out by Iraqi laid, UK made barmines during breaching operations on the first day of the ground war. The Marines lost one other tank to friendly fire. See "Braving the Breach," by LTCOL J. G. Zumwalt, Naval Institute Proceedings, July 1992, pages 75-77 and "2D Marine Division Breaching Operations During Desert Storm," LTCOL Mark Swanstrom, April 1991, page 7.

[e] "After Action Report, Operation Restore Hope," by William C. Schneck, Belvoir RD&E Center, Ft Belvoir, Virginia, 13 June 1994, Appendices B & D, and "Quick Reaction Force, Falcon Brigade, 10th Mountain Division, Summary of Combat Operations on 3 October 1993," by COL Lawrence Casper, 10th Aviation Brigade, Mogadishu, Somalia, undated.

[aa] "Task Force Eagle Mine Strike Summary" as of 5 August 1996. The US has lost 1 M728 CEV, 2 Bradleys, 2 Panthers, and 1 HMMWV to mines. Except for the HMMWV, all vehicles were repairable.

TABLE A-6: US ARMY GROUND PERSONNEL WOUNDED IN ACTION (WORLD WAR II TO PRESENT)[a]

(1) THEATER	(2) TOTAL HOSPITALIZED	(3) ESTIMATED TOTAL WIAs (KNOWN ENEMY MUNITION)	(5) ESTIMATED TOTAL TANK CREW WIAs[b]	(7) ESTIMATED TOTAL MINE WIAs[c]	(10) PERCENT MINE WIAs[d]
WWII (OVERALL)	599,724	507,873	8,247	25,529	5.0%
WESTERN EUROPE	393,987	334,889	6,251	15,759	4.0%
MEDITERRANEAN	107,323	91,223	1,403	5,366	5.0%
PACIFIC	93,202	78,886	593	1,529	1.6%
KOREA	66,547	65,170	-	2,451	3.6%
VIETNAM	197,378	167,771	-	56,783	34%
PERSIAN GULF[e]	467	56	-	14	3.0%
SOMALIA	137	9	0	9	6.5%
BOSNIA	4	4	0	4	100%
TOTAL	864,437	740,883	8,247	84,790	11%

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[a] Data taken from Conventional Warfare, Ballisitc, Blast, and Burn Injuries, Table 2-9, page 63 for WWII & Table 2-11, page 64 for Korea .

[b] Data taken from Table A-5, column 9.

[c] Column 5 plus "Mines" row in Tables A-7 & A-8.

[d] Column (7) divided by column (3).

[e] Includes USMC casualties

TABLE A-7: US ARMY CASUALTIES WOUNDED IN ACTION IN WORLD WAR II, BY MUNITION[a]

	(1) WESTERN EUROPE	(2) MEDITERRANEAN	(3) SOUTHWEST PACIFIC	(4) PACIFIC OCEAN AREA	(5) OVERALL PACIFIC[b]	(6) TOTAL[c]
HOSPITALIZED	393,987	107,323	59,646	33,556	93,202	599,724[d]
WIAs BY KNOWN MUNITION	334,889	91,223	50,699	28,187	78,886	507,873
BOMBS	3,940 (1%)	2,146 (2%)	1,789 (3%)	1,007 (3%)	2,796 (3%)	8,882 (1.5%)
SHELLS	232,452 (59%)	66,540 (62%)	24,455 (41%)	16,442 (49%)	40,897 (44%)	339,889 (57%)
BULLETS	74,858 (19%)	15,025 (14%)	19,087 (32%)	9,731 (29%)	28,818 (31%)	118,701 (20%)
MINES[e]	15,759 (4%)	5,366 (5%)	1,193 (2%)	336 (1%)	1,529 (1.6%)	25,529 (5.0%)[aa]
GRENADES	7,880 (2%)	2,146 (2%)	4,175 (7%)	671 (2%)	4,846 (5%)	14,872 (2.5%)

[a] Data taken from Conventional Warfare, Ballisitc, Blast, and Burn Injuries, Table 2-9, page 63.

[b] Column (3) plus column (4).

[c] The sum of columns (1), (2), & (5).

[d] Appears to include casualties incurred outside the theaters of operations specified.

[e] Considering that the initial data was rounded off to the nearest percentage point, the accuracy of the mine casualty figures is limited to ± 12.5%.

[aa] Conventional Warfare, Ballisitc, Blast, and Burn Injuries gives the total number of US WIA to mines as 25,529. This results in an overall rate of 5%., which is cslightly greater than that given in Warfare and Armed Conflicts, A statistical Reference, Volume II, by Michael Clodfelter, McFarland and Company, 1992, page 959, which gave an overall estimate of 3.4% WIA by mines plus 0.5% WIA by boobytraps.

TABLE A-8: US ARMY CASUALTIES WOUNDED IN ACTION SINCE WORLD WAR II, BY MUNITION

	KOREA[a]	VIETNAM[b]	PERSIAN GULF[c]	SOMALIA[d]	BOSNIA[e]	TOTAL[aa]
WOUNDED	66,547	197,378	467	137	4	264,533
WOUNDED BY KNOWN ENEMY MUNITION	65,170	167,771	56	9	4	233,010
SHELLS	36,379 (56%)	43,621 (26%)	42 (75%)	-	-	80,042
BULLETS	19,833 (30%)	41,943 (25%)	-	-	-	61,776
MINES	2,401 (3.7%)	56,783 (34%)	14	9	4 (100%)	59,211
GRENADES	6,557 (10%)	25,166 (15%)	-	-	-	31,723
OTHER	-	258	-	-	0	258
UNKNOWN	1,377	-	411	126	0	1,914

[a] Data taken from Conventional Warfare, Ballisitc, Blast, and Burn Injuries, Table 2-11, page 64.

[b] See the discussion at the end of this appendix for the method used to estimate the breakout of US casualties in Vietnam.

[c] Desert Shield/ Desert Storm, Army Times After Action Reports, 1991-1992.

[d] "After Action Report, Operation Restore Hope," by William C. Schneck, Belvoir RD&E Center, Ft Belvoir, Virginia, 13 June 1994, Appendices B & D, and "Somalia, December 9, 1992-March 28, 1994," Congressional Research Service.

[e] "Task Force Eagle Mine Strike Summary," as of 5 August 1996.

[aa] The following are not included in these totals, Grenada: 119 wounded, Panama: 320 wounded.

DISCUSSION

There are a variety of potential inaccuracies in this estimate of US mine casualties. The estimates, including accuracy of diagnosis of cause of death, identification of the ordnance responsible for the casualty, and data manipulation techniques used to obtain statistical estimates are of questionable reliability.

VIETNAM WAR MINE CASUALTY ANALYSIS

The Mine Warfare Center in Vietnam reported "An important observation is that the share of casualties reported as caused by mines and boobytraps is believed to be well below the actual fact. Specifically, it is believed that the classification of "fragmentation" as the cause of casualties in many cases obscures the fact that the fragmentation resulted from a mine or boobytrap explosion. Infantry divisions in the field experience a higher percentage of casualties resulting from mines and boobytraps. ...figures released by the 1st Marine Division and the 9th Infantry Division indicate that the mine and boobytrap share of their casualties fluctuates between 40% and 60% of the totals."[92]

Based on the primary source information provided by the Mine Warfare Center in Vietnam, medical corps estimates for mine casualties (contained in Assessing the Effectiveness of Conventional Weapons, Table 2-15, page 66) appear to be mistaken. There are a variety of reasons for the discrepancies. By their own admission, the medical corps acknowledges that its is often times difficult for medical personnel to properly identify the cause of a casualty. It would appear to be for this reason that U.S. CASUALTIES IN SOUTHEAST ASIA, Statistics as of November 11, 1986, page 10 lumps mines and grenades together and has a additional category labeled "multiple fragmentation wounds." The total number of KIAs given for these two categories is 11,471. Considering the large number of fragmenting mines encountered by the US Army in Vietnam (40% of the total encountered)[93] and the fact that this type of munition frequently causes multiple casualties, it would seem reasonable to reevaluate the breakdown of the causes of casualties in this light.

ESTIMATION METHOD

Total US Army combat casualties (KIA plus WIA) were assumed to be 26,259 KIA plus 303,659 (total US DOD hospitalized) times .65 (fraction of Army KIA of DOD total) times .85 (fraction of combat casualties to enemy ordnance). This produces an estimate of 194,030 total US Army combat casualties and 167,771 total US Army WIA.

Based on information from the Mine Warfare Center in Vietnam, total US Army mine casualties were estimated as .33 (fraction of combat casualties to mines) times 194,030 total US Army combat casualties. This produces an estimate of 64,029 total US Army mine casualties. Using the ratio .113 mine KIAs per mine WIA from the Mine Warfare Center's data, this breaks down to 7,246 US Army mine KIAs and 56,783 US Army mine WIAs. Grenades are assumed to account for the rest of the US Army KIAs (4,225).

The WIA fraction for each munition type was estimated to be shells-.26, bullets-.25, grenades-.15. The number of WIAs by type of munition was determined by multiplying the appropriate fraction by the total US Army WIA figure of 167,771.

APPENDIX B
THE ORIGINS OF MILITARY MINES

Early mining techniques were developed in response to walled cities in the Middle East which were themselves developed as protection against raiders and other threats. Jericho is the oldest known example of a walled city (dating from approximately 7,000 B.C.). Prior to the introduction of mining, the attacker's options were limited to blockading the city (starve them out), scaling the walls, breaching the walls with a battering ram (which first appeared in Egypt about 2000 B.C.),or by stratagem (for example, the Trojan Horse). Early mines were used both offensively and defensively. Their use has evolved considerably through the 3000 years of warfare since their introduction. This evolution includes the emergence of explosive tunnel mines, fougasse, self-contained mines (both antipersonnel and antitank), boobytraps, and sea mines.

THE EARLIEST MINES

The Assyrian Army, with its iron pioneer tools, is credited with the first known use of mines in warfare. This occurred around 1000 B.C. and consisted of tunnels (mines) driven beneath the foundations of walls and fortifications.[94] These mines could then be used by soldiers to gain access to the interior of a fortified area or they could be used to create a breach large enough for a full scale attack by collapsing a section of a wall. This was done by excavating a chamber under the wall while bracing the ceiling with timber supports. These supports were then burned, which caused the collapse of the chamber and the structure above it. Attacking soldiers then assaulted through the resulting breach. Many such mines have been mentioned in history, notably the successful mines used by Alexander the Great at the sieges of Halicarnassus (334 B.C.) and Gaza (332 B.C.)[95] as well as Julius Caesar during the siege of Marseilles in 49 B.C.[96] Effective mining (and other engineering skills) was critical to the military successes of both men.

EARLY OBSTACLES

During the siege of Alesia (52 B.C.), Julius Caesar's engineers emplaced a 100 meter deep combination of towers, pallisades, ditches, abatis, and caltrops to slow down attacking Gauls so that they could be more effectively engaged by Roman missile weapons. These obstacles also gave Caesar the time needed to successfully deploy reserve forces to threatened areas along his 13 mile long perimeter.[97] Other examples of early obstacles include the abatis emplaced by the English longbow men for protection against the mounted French Knights at Battle of Agincourt in 1415.[98]

EXPLOSIVE MINES

The advent of the capability to manufacture and detonate black powder (in Europe this occurred in the 14th century) resulted in the next major improvement in military mining. These mines were defined by the depth and size of the charge as follows:

-For depths greater then than 3 meters, it was called a "mine"
-For depths less than 3 meters underground, it was called a "fougasse" (or contact mine)
-When used as a "countermine" against an enemy mine, it was called a "camouflet"
-When intended to destroy an entire fortification (using 2,500 kilograms of powder or more), it was called "pressure balls" (globes de compression)[99]

TUNNEL MINES

The effectiveness of tunnel mines was significantly increased by exploding large charges of black powder at the end of the galleries driven under fortifications. The first recorded use of such a "mine" in Europe was in 1403 during a war between Pisa and Florence, when the Florentines exploded a charge in a forgotten walled up passage in the walls surrounding Pisa.[100] In his famous work on siege warfare (published in 1770) Sebatien Le Prestre de Vauban (French Marshal, 1630-1707) codified the principles of military mining that remained valid well into the nineteenth century.[101] The number and locations of demolition chambers were dictated by the type of fortification. According to Vauban's tables, explosive charges for mining could range up to 26,690 pounds. The purpose of the mine was not only to cause destruction, but also - with the rocks and soil ejected - to form a breaching ramp that the assault troops could use. Moreover, the demolition often came as a surprise to the defending forces, causing panic and confusion among the defenders.

Tunnel mines were very time consuming to employ. Military mining during a siege could last 30 days or more. Furthermore, specialists were required for the job. At first, coal miners were hired. It was not until standing armies were raised by the absolute monarchs of the 17th century that formal mining units were formed (1673 in France, 1683 in Austria). Their work demanded courage and special caution. Lack of oxygen and possible flooding made their job difficult. Eighteen miners and 36 unskilled workmen were normally employed in three eight hour shifts to construct an assault mine.

Mining was begun as soon as sappers had completed the last parallel in front of the glacis of a fortress or fortified town. The besieging miners dug galleries, about 1.25 meters high and 1 meter wide, lined with wood. Once the miners had reached the selected site for the explosion, they dug out the blast hole perendicular to the previous direction of the gallery. This mine chamber was then filled with the amount of black powder determined by the siege engineer.

To ignite the mine, an ignition "sausage" was fed out of the mine chamber. This sausage was a tube made of linen and filled with granulated powder, leading back to the point of

ignition (minenherd). This ignition sausage was laid in 6 cm wide wooden duct, covered with a board, to protect it from moisture on the floor of the mine gallery, or other damage. The gallery was finally tamped with sod or earth, over a length of 6 to 10 meters. The miner ignited the granulated powder in the ignition sausage with an ignition sponge at the appointed time, and then retreated quickly before the ignition sponge had burned down to the granulated powder.

Immediately after the explosion, the besiegers could assault the fortress or extend their sap trenches into the crater and reinforce them with gabions. If necessary further mines were used to take the pallisades of the covered passage, the supporting walls of the counterscarp or the scarp thus facilitating entry into the fortress.

While working in the tunnels, attention had to be paid at all times to listening tunnels and the countermines of the defender. The attackers tried to deceive the listening posts by constructing phony galleries, in which workers produced a lot of noise (noise gallery).

As they became available, military engineers incorporated the latest technology from civilian mining, more efficient munitions (picric acid in 1843, nitrocellulose in 1845, and TNT in 1904), galvanic ignition (1860s), and ventilation systems. During World War I, both sides employed mechanical tunnel boring machines.

This type of tunnel mining has continued into the modern era and has been used by Napoleon at Acre (1799) , in the American Civil War (Vicksburg[102] and Petersburg[103]), Russo-Japanese War (Port Arthur[104]), World War I (Western Front[105] and the Isonzo Front[106]), World War II (Russian Front[107]), French-Indochina War (Dien Bien Phu[108]), and may be employed by the North Koreans in some future war considering that some tunnels under the DMZ (De-Militarized Zone) have been discovered and more are suspected.

FOUGASSE[109]

Frederick the Great, King of Prussia, remarked "Fougasses formed into a T like mine, in order to blow up the same place three times, can be added to the intrenchments. Their use is admirable: nothing fortifies a position so strongly nor does more to ward off attackers."[110] These fougasses were simple black powder devices that were first developed for the defense of permanent fortifications. They were supposed to be detonated in the face of an enemy assault. A black powder charge was placed in a chamber excavated in the face of a fortification or in front of it. The chamber was then packed with a large amount of fragments (normally just rocks or scrap iron). If properly emplaced, it functioned as a crude claymore type mine. The fougasse was command detonated by manually igniting a powder train from a protected position at the appropriate time. Fougasses suffered from obvious defects, not the least of which was its vulnerability to the elements; even moderate dampness would render the fougasse inoperative. In the right circumstances they could cause a large number of casualties as occurred during the sieges of Ciudad Rodrigo, Badajoz, and Santander in the Peninsular Campaign of the Napoleonic Wars.

Fougasses were employed by George Washington's engineers at Forts Mifflin and Mercer on the Delaware River during our Revolutionary War.[111] The Mexicans also attempted to employ them on the approaches to Chapultepec during the Mexican-American of 1845.[112] Fougasses are still occasionally employed by irregular forces, such as the Viet Cong,Central American guerillas,[113] and Bosnians[114] that lack access to modern landmines.

SELF-CONTAINED ANTI-PERSONNEL MINES

Military engineers in China produced and employed the first self-contained explosive antipersonnel mines for use against the Mongol invaders in 1277. These mines were manufactured in many shapes and sizes.

The introduction of the first European flintlock in 1547 was the basis for the first fuzed anti-personnel mine in the west. This was the fladdermine which was developed by Samuel Zimmermann of Augsburg in 1573.[115] It consisted of one or more pounds of explosive buried at a shallow depth in the glacis of a fortress and was actuated by somebody stepping on it or activating a trip wire strung low along the ground This released a flintlock igniter which fired the main charge. Like the Fougasse before it, these devices were highly vulnerable to dampness and were only practical for use around fixed fortifications.

The introduction of the explosive shell in the 1700s (1221 in China) and the percussion cap by the British in the 1820s made possible the next important step in the development of mines. Confederate soldiers, under the leadership of General Gabriel Raines improvised the AP mines from artillery shells near Yorktown, Virginia during the campaign of 1862.[116] By the end of the Civil War, the Confederates had emplaced thousands of "land torpedos" around Richmond Virginia, Charleston South Carolina, Mobile Alabama, Savannah Georgia, Wilmington North Carolina, and Atlanta Georgia producing hundreds of casualties. Their use was advocated by such famous soldiers as Robert E. Lee, John Mosby, and J.E.B. Stuart.

The tretmine (step-on mine) was the next mine of this type to appear. It went into production before World War I. However, the near domination of infantry by artillery and the machine gun meant that the need for AP mines received little attention from the warring powers.

The origin of each specific type of AP mine is discussed under the appropriate heading in the text. The antipersonnel mine reached full maturity during World War II and has been a facet of almost every conflict since.

ANTITANK MINES

German combat engineers improvised the first antitank mines during WWI in response to the appearrance of the tank. Initially, they used existing artillery and mortar shells with

sensitive fuzes. Later, they improvised wooden box mines, each weighed about 12 pounds and consisted of 20 powder charges of 200 grams each. These were placed in boxes approximately 14 X 16 X 2 inches and were concealed about 10 inches deep. Detonation was caused by a hand grenade placed inside and against one of the walls so that the primer passed through the wall. It could function automatically as the tank passed over it or by command detonation (which was greatly facilitated by the use of electric blasting caps which first appeared in 1900).[117] These AT mines were scattered at random to reinforce wire obstacles and antitank ditches in front of the trench lines. The Germans also began to manufacture antitank mines in 1916 and produced almost 3 million before the Armistice of 1918.

The Germans developed and fielded the first full width attack mine toward the end of World War II. It employed a tilt rod and shaped charge kill mechanism. Improvised side attack AT mines were first employed by the Germans and Russians on the Eastern Front in World War II. Like the anti-personnel mine, the antitank mine reached full maturity during World War II and has been a facet of almost every conflict since.

BOOBYTRAPS

The first explosive boobytraps were employed by the Chinese against the Mongols in 1277.[118] The first appearance of explosive boobytraps in the West occurred during the Seminole War of 1840.[119] These were also employed in limited numbers by the Confederates during the Civil War. The Confederates employed a variety of devices including pull firing devices, timer run, and coal and wood "torpedoes" which detonated when burned in a boiler etc. With the introduction of reliable mechanical devices during World War II, the boobytrap reached full maturity and has been a facet of almost every conflict since.

COUNTERMINES

The original countermines were mines dug by the defender to disrupt enemy mining efforts. Countermines were employed frequently to defeat enemy mining efforts when they were detected. Before the advent of black powder, a successful countermine resulted in the interception of an enemy tunnel and produced a confused, close quarters underground fight, as the two sides fought for control of the tunnel.[120]

John Vrano was the first to use black powder in a countermine against the Turks during the siege of Belgrade in 1433.[121] In this application, the intent was to dig down close to the enemy's mine gallery and emplace/detonate a charge that would collapse his tunnel and kill the miners. During the Thirty Years War, poisonous antimony gas was released into the tunnels to kill the miners. The use of this type of countermine has continued up to the First World War.

Modern countermine equipment first appeared at the end of World War I as the British and French attempted to find a countermeasure to protect their tanks from German antitank mines. Except for some of the advanced electronic systems currently in development, most countermine concepts currently in use appeared before or during World War II.[122] One of the most highly developed countermine organization was the British 79th Armored Division which consisted of nothing but special purpose armored engineer vehicles.[123]

SEA MINES

The Chinese first employed sea mines in the fourteenth century. The oldest known European plan for a sea mine was presented by Ralph Rabbards to Queen Elizabeth in 1574.[124] The first known employment of sea mines in the west occurred in 1777 when an American Army engineer, David Bushnell, attacked British ships on the Delaware River with floating mines.[125] Robert Fulton and Samuel Colt both became interested in sea mines but lost interest when their experiments were not well received. Although, floating mines were used during the Crimean War by the Russians in 1855 and at Canton, China in 1857-58, their first significant employment occured during the American Civil War, where they were responsible for most of the Union ships sunk.[126]

ANTIAIRCRAFT MINES

The first improvised anti-helicopter mines appeared during the Vietnam War and were used to cover potential landing zones.[127] Many manufacturers now offer this type of mine. During the Cold War, the Russians developed an antiaircraft mine based on their SA-7/14.[128] The British and the Americans are developing "smart" anti-helicopter mines that can be deployed to engage low flying helicopters.[129] Some of the technologies being developed for the Ballistic Missile Defense Office could, in fact be consider orbiting mines.

APPENDIX C
AP MINE EFFECTIVENESS

The recent debates on the effectiveness of AP mines have focussed strictly on their significant attritional characteristics. As shown in Appendix A, they have proven highly effective in this area.[130] In Vietnam, they accounted for 33% of US combat casualties. As a result of this, AP mines are often viewed as defensive weapons suited only for old fashioned attrition warfare. Indeed, unskilled armies often use them in this fashion. There is also an important synergistic effect between mines and other weapon systems. By slowing down and channelizing the enemy, mines increase enemy exposure to the direct and indirect fires that normally cover an obstacle. In the same vein, AP mines are frequently used to protect AT mines from breaching by dismounted sappers. This technique was used by one USMC battalion during the Gulf War.[131]

Nevertheless, this narrow view overlooks the primary benefit of integrating AP mines with the combined arms team, which is their ability to decrease the operational tempo of dismounted enemy forces by undermining his moral.[132] As General Patton observed, "The effect of mines is largely mental."[133] This is a very important effect because the US doctrine of victory through maneuver warfare rests on exploiting the enemy's key psychological weaknesses. As Napoleon remarked, "The moral is to the physical as three is to one." A key result of making the enemy fear mines is the increased time it takes him to move. It has been estimated that for conventional maneuver units conducting mounted operations that 100 anti-track mines per km of front decrease the rates of advance by 40%, 500 anti-track mines per km by 50% and 1000 anti-track mines per km by 60%.[134] This gives US forces more time to exploit fleeting opportunities as they appear on the battlefield. As Napoleon remarked, "The loss of time is irreparable in war."[135]

Consider the following example, "(T)he road out of Normandy was indeed mined, considerably more than the Carentan area had been. I don't remember anyone getting killed on the road, but we lost two trucks and a tank had to be retreaded. The worst part of these explosions was that they made us acutely aware of their potential and their probable numerousness. This was the excruciating aspect of those first few days. You stare at the ground and wonder where not to walk. What part of this dust, or this rich loam, carries death within it?"[136]

Field Marshal Rommel, the great "Desert Fox," understood the effects of mines better than most as he demonstrated in preparing for the Second Battle of El Alamein. "We wanted to ensure that the work of clearing the minefields proceeded at the slowest possible speed and not until after our outposts had been eliminated. Most of the mines available in Africa were unfortunately of the anti-tank type, which infantry could walk over without danger. They were, therefore, comparatively easy to clear." [137] However, in some of the sectors where the limited number of AP mines available were employed effectively, the attacking forces were either stopped (7th Armored Division) or severely retarded (1st South African Division). After the defeat of Rommel's badly outnumbered Afrika Korps at El Alamein, the skillful use of mines by the German pioneers (combat engineers) to exploit terrain conditions was critical to the successful escape of the Afrika Korps from Montgomery"s 8th Army.[138] Later, when faced with the daunting task of defending the Atlantic coast, Rommel requested 50 million mines but had only received/emplaced about 5-6 million by D-Day.[139] Nevertheless, the critical landing on Omaha Beach nearly failed because the US 1st and 29th Infantry Divisions could not get off of the beach in part because of the AP mines.[140]

At Kursk, the Russians skillfully integrated AP mines within their defensive zones to separate the General Model's Panzers, particularly the Tigers, Panthers and Elephants from their accompanying infantry and combat engineers, thus breaking up the German combined arms team. By slowing down the German advance, the Russian were able to mount counterattacks that eventually halted the German spearheads.[141]

The fielding of long-range mine scattering systems has enhanced the ability of ground combat forces to use mines offensively, the decisive form of combat. These systems can be used to separate dismounted elements from mounted units, to delay the arrival of reinforcements and disrupt the synchronization of an opponent. They can also be used to deny an opponent access to key facilities such as airfields and Nuclear, Biological and Chemical weapons storage sites (as was done during the Persian Gulf War) which could contaminate a large area if they were attacked with precision guided munitions.

Considering that the only conflicts in which the US Army has not achieved a resounding victory in the 20th century were against dismounted opponents in Korea and Vietnam, the willingness of some individuals to deny the use of AP mines to our soldiers is morally and militarily questionable. Furthermore, our most likely military operations for the foreseeable future will be against just such dismounted opponents. As the great military philosopher Carl Von Clausewitz noted "Kind-hearted people might of course think there was some ingenious way to disarm or defeat an enemy without too much bloodshed, and might imagine this is the true goal of the art of war. Pleasant as it sounds, it is a fallacy that must be exposed: war is such a dangerous business that the mistakes which come from kindness are the very worst. The maximum use of force is in no way incompatible with the simultaneous use of the intellect."[142]

APPENDIX D
AP MINE INVENTORY PROFILES

TABLE D-1: IRAQ

BLAST	VS-50, PRB M409, SB-33, PMN, TYPE 72
BOUNDING	VALMARA 59 & 69, P-40
DIRECTIONAL	
SIMPLE FRAG	P-25

TABLE D-2: NORTH KOREA

BLAST	PMN, PMK-40, PMD series
BOUNDING	OZM-3
DIRECTIONAL	
SIMPLE FRAG	POMZ-2, Improvised
OTHER	Expedient flame mine

TABLE D-3: BOSNIA

BLAST	PMA series
BOUNDING	PROM series, PSM-1
DIRECTIONAL	MRUD
SIMPLE FRAG	PMR series

TABLE D-4: UNITED STATES

BLAST	M 14 (3,500,000)
BOUNDING	M 16 (1,500,000) ADAM (5,947,200) PDM (16,800)
DIRECTIONAL	M 18 (973,932)
SIMPLE FRAG	VOLCANO (107,300) MOPMS (9,200) GEMSS (71,200) GATOR (USAF) (238,612) (USN) (45,375)

TABLE D-5: AP MINE OCCURRENCE BY CONTINENT[143]

ASIA:

AFGHANISTAN (9-10 million):PMN series, OZM series, MON series, POMZ-2, PFM-1, PMD series, PP-MI-SR, M 18

IRAQ (5-10 million): see Table C-1

CAMBODIA (4-7 million mines):PMN series, OZM series, MON series, POMZ-2, PMD series, PP-MI-SR, M 14, M 16, M 18, Type 72, PMA series, Valmara 69, PPM-2

AFRICA:

ANGOLA (9 million): PMN series, OZM series, MON series, POMZ-2, PMD series, PP-MI-SR, M 14, M 16, M 18, Type 72, PMA series, PMR series, Valmara 69, VS-50, VS-Mk 2, PPM-2

ERITREA/ETHIOPIA (300,000 TO 1 million): PMN series, OZM series, MON series, POMZ-2, PMD series, M 3

MOZAMBIQUE (2 million):PMN, POMZ-2, PP-MI-SR, M 18

SOMALIA (1-1.5 million):PMN, POMZ-2, PMD series, PP-MI-SR, M 14, M 16, Type 72, PPM-2

SUDAN (500,000 TO 2 million): "Older Soviet"

EUROPE:

BOSNIA (1-1.7 million): See Table C-3

CENTRAL AMERICA:

EL SALVADOR (20,000), M 14, M 18, improvised mines

HONDURAS: PMN series, PMD-6, PP-MI-SR

NICARAGUA(116,000): PMN series, PMD-6, MON series, POMZ-2, PP-MI-SR

GUATEMALA: M 18, improvised mines

WORLDWIDE OVERVIEW[144]

Most common AP mine: PMN
Typical directional mine: MON-50
Most lethal directional mine: MON-200
Typical bounding mine: OZM-72
Most common stake mine: POMZ-2M
Most difficult to detect: PMA-2

ENDNOTES AND REFERENCES

1. The Viet Cong successfully did this in Vietnam. The Iraqis also attempted to exploit our vulnerability to mines but failed to secure their open flank. This paper is adapted from "The Vehicular Mine Threat," by Harry Hambric and William Schneck, Proceedings of the Sixth Annual TARDEC Combat Vehicle Survivability Symposium (U), May 1995, Volume 1, pages 53-99.

2. Although mines are viewed by the Army as an "engineer or EOD problem," the vast majority of mine casualties occur in other combat arms and support units. Another item not reflected in these statistics is the synergistic effect of mines, whereby the presence (or fear) of mines slows down US forces and increases their exposure and casualties due to other enemy weapons. See Antiarmor Tactics and Techniques for Mechanized Infantry, TC 7-24, Headquarters, Department of the Army, 30 September 1975, page E-4.

3. "After Action Report for Operations Desert Shield and Desert Storm," US Army Engineer School, Ft Leonard Wood, Missouri, July 1993, page Countermobility-4.

4. Jane's Military Vehicles and Logistics, 1991-1992, Jane's Defence Data, 1991, pages 143-206. It can be argued that advanced mines represent the ultimate in smart weapons. They do not detonate until such a time as they can damage a target, are extremely difficult to counter, can be fitted with IFF (Identify Friend or Foe), self destruct/ neutralization, while minimizing the exposure of the emplacing force to enemy countermeasures.

6. "Advances in Mine Warfare: An Overview," by William C. Schneck, Malcolm H. Visser, & Stuart Leigh, Engineer Professional Bulletin, Ft Leonard Wood, Missouri, April 1993, page 3.

7. The section on mines is adapted from "Advances in Mine Warfare: Anti-personnel Mines," by William C. Schneck, Malcolm H. Visser, & Stuart Leigh, Engineer Professional Bulletin, Ft Leonard Wood, Missouri, August 1993, pages 26-33.

8. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992, pages 143-206. Mines rarely introduce "cutting edge" technologies, rather they exploit technologies developed for other higher profile weapon systems.

9. Mine Recognition and Warfare Handbook, US Army Engineer School, Fort Leonard Wood, MO, November 1990. Contrary to USAF statements, attempts to breach minefields by bombing (including the use of Fuel-Air Explosives (FAE)) were not effective. It should be noted that FAE was intended to expose shallow buried mines through their differential inertial response, and then deal with them by some other means such as direct fire. See The United States Army Engineer After Action Report for Operations Desert Shield and Desert Storm, page Mobility-18 and "After Action Report, Operations Desert Shield and Desert Storm," William C. Schneck, Belvoir RD&E Center, 12 November 1991, page 10.

10. Land Mines, TM 9-1940, Headquarters, Department of the Army, Washington, D. C., 15 July 1943.

11. Viet Cong Boobytraps, Mines, and Mine Warfare Techniques, TC 5-31, Headquarters, Department of the Army, December 1969.

12. Mine/Countermine Operations, FM 20-32, Headquarters, Department of the Army, September 1992, page D-18.

13. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992.

14. Significant Landmines and Booby Traps Employed by US and Allied Forces, 1940-1970, Landmine and Countermine Warfare, Engineer Agency for Resources Inventories, Washington, D.C., June 1972, page 6. The first directional mine was prototyped by the Germans in WWII, see Claymore Mines, Their History and Development, by Larry Grupp, Paladin Press, Boulder Colorado, 1993, page 29.

15. The US defines the lethal range (or radius) of a munition as that distance where there is one lethal fragment (58 ft-lb) per square meter, One square meter is the approximate frontal area of the average standing soldier. Non-directional mines that produce fragments in all directions are defined in terms of lethal radius instead of range. See also Wound Ballistics, CMH Pub. 81-34, Office of the Surgeon General, Department of the Army, Washington, D.C., 1962, page 93.

16. The MON-200 projects 900 12mm X 12mm mild steel cylinders (approx. 165 grains each) with a maximum velocity of about 4500 fps (about 4000 fps average). The MON-100 projects 400 10mm X 10mm mild steel cylinders (approx. 95 grains each). The MON-90 projects 2000 7mm X 7mm mild steel cylinders (approx. 33 grains each). The MON-50 projects 485 5mm X 5mm mild steel cylinders (approx. 12 grains each) or 540 spherical fragments. The existence of a MON-500 has also been reported. Classified mass/velocity profiles for the US M16, M18 and M-26 are available in Fragmentation Characteristics and Terminal Data for Surface to Surface Weapons (U), FM 101-62-3, Joint Munitions Effectiveness Manual, 1 July 1982, pages 3-141 to 3-142.

17. German Mine Warfare Equipment, TM 5-223C, March 1952, pages 123-129. This mine was first encountered by the West during the "Phony War" in 1939 when French patrols began to suffer unexplained casualties. The French dubbed their nemesis the "silent soldier." Engineers in Battle, by Paul Thompson, The Military Service Publishing Company, Harrisburg, PA, 1942, pages 64-65.

18. OP CIT, Mine Recognition and Warfare Handbook, page 196 & 197.

19. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992.

20. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992, page 172.

21. Eastern Europe, World War II, Landmine and Countermine Warfare, Engineer Agency for Resources Inventories, Washington, D.C., August 1973, page 155.

22. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992, page 199.

23. The Soviet Army; Troops, Organization, and Equipment, FM 100-2-3, page 5-166.

24. Gulf Air War Debrief, Edited by Stan Morse, World Air Power Journal, Airtime Publishing Inc., Westport, Connecticut, 1991, page 64.

25. OP CIT, "After Action Report, Operations Desert Shield and Desert Storm,", pages 13 - 15. See also Multiservice Procedures for Operations in an Unexploded Ordnance Environment, FM 100-38, July 1996, Appendices C, D, & E.

26. OP CIT, Mine Recognition and Warfare Handbook, pages 70, 80, 82, & 138-143. It appears that the UDAR is intended to breach its own minefields to open up counterattack routes.

27. Chemical Warfare in World War I: The American Experience, 1917-1918, by Charles Heller, Leavenworth Papers No. 10, Combat Studies Institute, Ft Leavenworth, Kansas, September 1984, page 20-21.

28. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992, pages 191 & 201. The Germans also produced (but did not use) chemical mines during WWII. See Handbook on German Military forces, TM-E 30-451, War Department, Washington, D.C., 15 March 1945, page 532.

29. OP CIT, FM 20-32, 1992, pages 12-9 to 12-11.

30. Principles of Improvised Explosive Devices, Paladin Press, Boulder, Colorado, 1984.

31. Boobytraps, FM 5-31, Headquarters, Department of the Army, September 1965.

32. Engineer Contingency Handbook (Former Yugoslavia), US Army Engineer School, Ft Leonard Wood, MO, 1993, pages 1-35 to 1-37.

33. Iran, Libya and Syria must also be considered.

34. North Korean People's Army Handbook, FC 100-2-99, Battle Command Training Program, Ft Leavenworth, Kansas, 17 April 1992, pages 10-27 to 10-36. See also North Korean Military Forces, FM 34-71, Headquarters, Department of the Army, 5 February 1982, page 13-4.

35. OP CIT, Mine Recognition and Warfare Handbook.

36. OP CIT, "After Action Report, Operations Desert Shield and Desert Storm," William C. Schneck, Belvoir Research, Development and Engineering Center, 12 November 1991, pages C-1 & C-2. The intelligence community actually estimated that approximately 75 mine types from 13 countries constituted a threat to US forces during the Gulf War, indicating how unsure the US is of many potential opponents' mine inventories.

37. "Advances in Mine Warfare: Antitank Mines," by William C. Schneck, Malcolm H. Visser, and Stuart Leigh, Engineer Professional Bulletin, November 1993, pages 38-45.

38. The type of mining employed by guerillas during OOTW may also be encountered by rear area units conducting conventional operations (for example: mining operations by French and Russian partisans against the Germans during WW II or by the North Koreans against the US during the Korean War).

39. Protective minefields are normally present around all defensive positions that have been occupied for more than a couple of hours.

40. A detailed discussion of current US obstacle doctrine is beyond the scope of this paper. For more information see Combined Arms Obstacle Integration, FM 90-7, Headquarters, Department of the Army, 29 September 1994, pages 2-4 to 2-7. The obstacle "intent" must be confirmed through war gaming.

41. Manually emplaced mines may also be encountered in nuisance minefields that are laid by withdrawing units or as part of cross-FLOT (Forward Line of Troops) operations. Additionally, many countries employ dummy minefields to stretch available mine stocks or confuse the enemy about possible counterattack routes. For dummy minefields to be effective, the enemy must be "sensitized" to the mine threat.

42. The best available references for mine warfare in OOTW are TC 5-31 and the four volumes on Vietnam in the Mine/Countermine series. For urban mining, see "French Army Combat Engineer Experience in Beirut, Lebanon, February 1985," French War College Report 01-85, and for Mogadishu, "After Action Report, Operation Restore Hope," by William Schneck, Belvoir RD&E Center, 13 June 1994.

43. Although Vietnam occasionally had conventional features, it would be treated as an OOTW under current US Army doctrine.

44. Admittedly a rather generous description of the opportunistic route mining and other techniques they employed.

45. Sapper Countermine Guide, BRDEC Pamphlet 350-4, Belvoir Research, Development & Engineering Center, 30 November 1990, page 9.

46. It is claimed in Landmines, A Deadly Legacy, page 155, that the "great majority" are antipersonnel. This may well be true in rugged countries like Cambodia and Nicaragua where internal conflicts have been fought by dismounted soldiers but it is of questionable accuracy for desert areas or more advanced belligerents using motorized forces. This exaggerated claim lacks perspective and may be part of a disinformation campaign in support

of efforts to ban the antipersonnel mine. For example, see Tchad Liban, 1986-1988, Deminage-Depollution-Depiegeage, 17eme Regiment du Genie Parachutiste, page 45. Over 80% of the mines cleared by the French engineers were AT mines. In conventional operations, the mix of AP mines in US scatterable minefields typically ranges from 17% to 25%, depending on the emplacement system used.

47. "DOD Scientific and Technical Intelligence (S&TI) Support to International Mineclearing Programs," Briefing by Tom Reeder, Foreign Science and Technology Center, Charlottesville, Va., view graph #3.

48. Typical of downward ejected helicopter emplaced minefields like the other Italian systems, the US M-56, and the Russian PKPI.

49. Typical of vehicle dispensed minefields like Istrice, Minotaur, and Volcano.

50. Other MRLs in service/available that can scatter mines include the Astros II (Brazil) and one from Egypt. The Chinese have three other MRLs in service that can lay mines (Type 74, Type 79, and Type 81).

51. The VS-MDH and SY-AT systems are similar but carry 2080 or 3744 AP mines each respectively.

52. Minefield depth should be similar to that of the US M-56 system, about 40m. The typical length is about 270m.

53. Deployed with the UK during the Gulf War. They have a need for 30 to 50 launchers and 75,000 to 100,000 mines. The French plan to procure 60,000 mines for emplacement using the same launcher mounted on their EBG (combat engineer vehicle).

54. 126 EBGs ordered by the French army.

55. Minefield characteristics are probably similar to the US ADAM/RAAM system.

56. Minefield depth is probably similar to the US GATOR system, about 200m. The JP-233 is intended primarily for runway denial.

57. 300 ordered by the German army. Mine densities vary from .1 to .6 mines per meter of front. A UH-1 helicopter based system is also in development. This system can lay a 500m minefield in 20 seconds.

58. Germany has procured 1000 dispensers and Italy 100 Jane's Weapon Systems, 1987-88, Jane's Defence Data, 1987, page 767.

59. 209 launchers in service with the German army.

60. Licensed copy of the US MLRS. 59 launchers have been ordered by the British army. 150 launchers and 350,000 AT-2 (DM-1399) mines in MLRS rockets have been ordered by the German army. There are 28 mines per rocket, 12 rockets per launcher, & 9 launchers per battery.

61. GATOR density depends on whether the minefield is approached down the long axis or short axis. See FM 20-32 (1992), pages 6-11 to 6-13. See also FM 101-50-20, chapter 9.

62. Volcano minefields with a depth of 1.4 mines per meter are laid with a depth of 320m.

63. 41 systems were procured and deployed to Europe. They were consolidated in the Armored Cavalry Regiment and will be replaced by Volcano. The dispenser is carried by a UH-1 helicopter.

64. 69 procured and deployed with units in Europe and the US. Issued one per mechanized/armored division combat engineer company and augmented with the M-138 Flipper (174 procured) at a rate of 1 per platoon per company with GEMMS. Also issued separately to Airborne engineers. It is to be replaced by Volcano.

65. These numbers represent averages over the battle area and include successive belts of minefields. Local densities could vary significantly.

66. 486,000 mines (20% AP mines) on a 65 km front.

67. 800,000 total mines (48% AT mines). This was 6 times the density employed in the battle for Moscow (Nov/Dec 1941) and 4 times the density employed at Stalingrad (Oct/Nov 1942). See "Kursk, the Clash of Armor," by COL Koltunov, History of the second World War, Marshall Cavendish, page 1381.

68. For Omaha Beach, these mines were concentrated at the critical exits from the beach. See Breaching Fortress Europe, The Story of U.S. Engineers in Normandy on D-Day, by Sid Berger, Kendall/Hunt Publishing Company, 1994.

69. From Shield to Storm, by James Dunnigan and Austin Bay, William Morrow & Co., New York, 1992, page 359.

70. OP CIT, TC 5-31, page 5-3 to 5-9.

71. OP CIT, "After Action Report, Operation Restore Hope," page 56. The concepts for most of it dates from dates from World War I or II.

72. OP CIT, System Threat Assessment Report (STAR) For Family of Countermine Equipment (FACMS) (U), chapter 2. See also "The Vehicular Mine Threat," page 79 (Appendix E).

73. OP CIT, "After Action Report: Operations Desert Shield and Desert Storm."

74. Assuming the following standard equipment is on hand and the standard stockage of mines is available in the division. Additional support from higher headquarters would increase these figures. The typical Russian UBL for mines is 13,000 to 20,000 conventional AT mines and 20,000 to 30,000 AP mines per division. These figures do not include artillery and aircraft scattered mines. This equipment list is based on the standard Russian Tank or Motorized Rifle Divisions (TD, MRD) and the US Armored or Mechanized Divisions. Information for this table is taken from Battle Book, ST 100-3, Center for Army Tactics, CGSC, Ft Leavenworth, Kansas, page 6-1; Soviet Engineer Operations, Special Text, Ft Leonard Wood, Missouri, 5 January 1990, pages 3-1 to 3-43; and Engineer Systems Handbook, pages 38 to 63. There would be a natural tendency to exhaust the stock of high tech mines early in a conflict, thus forcing units to employ lower tech stocks later in a campaign. The typical frontage for a Russian MRD/TD attacking/ defending, 20 km and 20-30 km respectively. Minefield output for the Russians is based on 750 anti-track mines per km and 750 mines per kilometer of front (US) with a 50/50 mix anti-track/anti-hull. See also Countermobility, FM 5-102, Headquarters, Department of the Army, Washington, D.C., 14 March 1985. Other types of manmade obstacles (wire entanglements, blown bridges, road craters, log obstacles, etc.) are also possible (see Engineer Field Data, FM 5-34, Headquarters, Department of the Army, Washington, D.C., 14 September 1987, pages 3-1 to 3-15) however, the probability of encounter is difficult to estimate. Although wire obstacles are generally considered to be antipersonnel in nature, they are also capable of impeding vehicular movement. The effects of natural obstacles are covered in FM 90-7 (Final Draft), 1977, pages 3-5 to 3-19.

75. Limited primarily by UBL (Unit Basic Load).

76. The 3 combat engineer battalions assigned to US mech/armored divisions are capable of laying approximately 96 km of minefield per day but logistic capacity within the division will limit this to 75 km without significant corps level augmentation.

77. The Russians carry three loads per GMZ, UMZ, & PMZ-4.

78. A logistic surge of four reloads per day would yield 26.4 km per day.

79. The Russians typically attempt to keep 1.0 km of minelaying resources in reserve within a POZ (mobile obstacle detachment). The Russian are in the process of replacing the PMR-3s with GMZ armored mineplanters. The typical Russian MRD/TD will be able to mechanically emplace minefields at a rate of 11 km/hr.

80. Assumes a UBL of 456 rounds of RAAM per 155mm howitzer bn (battalion) (3 bns per division), 8 mines per round, the normal CSR (Controlled Supply Rate) is 8 rounds per bn per day during offensive operations and 16 rounds per day during defensive operations. Logistic surge capability or shortages could significantly alter this. The US is planning to employ WAM from either standard MLRS rockets or by ATACMS.

81. It is believed that the VMR-1 and VMR-2 have been retired from front line Russian divisions but may still be found in some client states.

82. The majority (nearly 100%) of the mines laid by the US and UK during the Persian Gulf War were emplaced by fixed wing aircraft. US F-111s dropped approximately 22,000 GATOR mines on 50 sorties during the first week of the air campaign. The US Navy also used GATOR to block the Iraqi retreat from Kuwait along the "Highway of Death" to establish this large kill zone at the end of the ground phase. UK Tornados emplaced approximately 43,000 HB-876 on 100 sorties during the first few days of the air campaign. See Gulf Air War Debrief, Edited by Stan Morse, World Air Power Journal, Airtime Publishing Inc., Westport, CT, 1991, page 218. CMS Inc. reported clearing 185 ADAM and 746 RAAM mines in their sector of Kuwait. This included the area through which the USMC maneuvered during the ground war. See "Unexploded Ordnance (UXO) Study."

83. Vietnam Lessons Learned, 1965-1968, Landmine and Countermine Warfare, Engineer Agency for Resource Inventories, Washington, D.C., July 1972. Some veterans of this conflict have argued that the US is in fact worse off in this respect as a number of specialized items and training courses used in Vietnam are no longer available. Currently there is little protection available to the "light" forces selected for operations other than war. A few special purpose mine resistant vehicle kits have been made available, primarily to special operations forces. Several mine resistant vehicle programs are currently underway. Their products are designed to significantly reduce crew casualties in both OOTW and conventional operations on a nonlinear battlefield. Some of these programs have demonstrated great promise.

84. Western Europe, World War II, Landmine and Countermine Warfare, Engineer Agency for Resources Inventories, Wash. D.C., 1973.

85. Advances in C4I (the "Information War") will mean little if the US can not maneuver to exploit it.

86. Infernal Machines, The Story of Confederate Submarine and Mine Warfare, by Milton F. Perry, Louisiana State University Press, 1965, pages 22, 166, and 205 (chapter V, note 1).

87. Historical Report of the Chief Engineer, American Expeditionary Forces, 1917-1918, Washington, D.C., 1919, page 241.

88. Mine/Countermine Operations at the Company Level, FM 20-32, US Army Engineer School, Ft Belvoir, VA, September 1976, page 135.

89. Unexploded Bomb, A History of Bomb Disposal, by A. B. Hartley, W. W. Norton & Company, New York, 1958, page 237.

90. Demining Operations (Initial Draft), TC 31-34, Headquarters, Department of the Army, Washington, D. C., July 1996.

91. And possibly stretch our limited countermine assets beyond the breaking point and producing battlefield paralysis.

92. "Mine Warfare in Vietnam," The Mine Warfare Center, Engineer Section, Headquarters, US Army Vietnam, August 1969, page 66.

93. OP CIT, TC 5-31, page 5-3.

94. The Art of Warfare in Biblical Lands, Volume 1, by Yigael Yadin, McGraw-Hill Book Company, New York, page 317.

95. The Generalship of Alexander the Great, by J.F.C. Fuller, Rutgers University Press, New Brunswick, N. J., 1960, pages 200-218.

96. War Commentaries of Caesar, by Julius Caesar, translated by Rex Warner, The New American Library, 1960, pages 259-266.

97. IBID, page 173.

98. The Face of Battle, by John Keegan, Penquin Books, 1976, pages 90-91.

99. "Siege," by Gert Bode, International Military and Defense Encyclopedia, Volume 5, Brassey's Inc., Washington, D.C., 1993, page 2421.

100. OP CIT, FM 20-32, 30 September 1976, page 133.

101. A Manual of Siegecraft and Fortification, Sebatien de Vauban, translated by George Rothrock, The University of Michigan Press, 1968.

102. "Engineer Operations During the Vicksburg Campaign," by Robert Puckett, AD-A255-141, Ft Leavenworth, KS, 1992, pages 124-132.

103. The Siege of Petersburg, by Joseph P. Cullen, Eastern Acorn Press, 1970, pages 17-23. The mine exploded by Federal troops under the Confederate earthwork at Elliot's Salient at Petersburg, Virginia, on 30 July 1864 was charged with 8,000 pounds of powder and produced a crater 9 meters (30ft)deep, 18 meters (60ft) wide, and 52 meters (170ft) long. The subsequent Federal assault, however, was unable to exploit the temporary advantage gained by the explosion and the surprise.

104. The History of Fortification, by Ian Hogg, St. Martin's Press, New York, pages 185-189.

105. War Underground, The Tunnellers of the Great War, by Alexander Barrie, Tom Donovan, London, England, pages 243-261. On 7 June 1917 British engineers fired nineteen mines with 430 tons of Ammonal at a depth of 40 meters at Wytschaete Salient south of Ypres, destroying three German battalions.

106. On 13 March 1918 Austrian engineers blew up part of Mount Pasubio, which was occupied by the Italians, using 50,000 kilograms (55tons) of explosive killing 485 men.

107. Small Unit Actions During the German Campaign in Russia, CMH Pub 104-22, Center of Military History, Washington, D.C., Facsmimile edition 1988, pages 165-168). The "Blitzkrieg" oriented German Army of WWII maintained special "Minier Pioniere" units throughout the war (Pioniere, Entwicklung einer Deutschen Waffengattung, by Dietrich Petter, Wehr und Wissen Verlagsgesellschaft MBH, Darmstadt, Germany, 1963, page 245).

108. Hell in a Very Small Place, by Bernard Fall, J.B. Lippincott Company, 1966, pages 384-386.

109. Not to be confused with the improvised flame mine that US Army engineers occasionally employ and call a "fougasse."

110. Frederick the Great, On the Art of War, by Frederick II, edited and translated by Jay Luvaas, copyright 1966, The Free Press, New York, page 288.

111. Engineers of Independence, A Documentary History of the Army Engineers in the American Revolution, 1775-1783, by Paul K. Walker, Historical Division, Office of the Chief of Engineers, Washnigton, D.C., page 158-159. Such devices are still occasionally encountered in modern warfare for example, see Engineer Field Manual, Parts I-VII, Professional Papers of the Corps of Engineers, U.S. Army, No. 29, Washnigton, D.C., 1918, pages 422 and 428.

112. The War with Mexico, by Donald Chidsey, Crown Publishers, New York, pages 161-163.

113. Ayudas de Instruccion Contra Minas, Trampas Y Artefactos Explosivos, Guatemalan Corps of Engineers, undated, page 60.

114. OP CIT, Engineer, Contingency Handbook (former Yugoslavia), page 1-32.

115. The Genius of China, by Robert Temple, Simon and Schuster, New York, 1986, page 235-237.

116. Lee's Lieutenant's, Volume 1, Douglas Southall Freeman, 1942, pages 268-269. See also Southern Historical Society Papers, Volume III, January to June 1877, Broadfoot Publishing Company, 1990 edition, pages 38-39. The sheels used were ordinary 8 or 10 inch mortar or columbiad shells. Such "land torpedoes" were also employed around Atlanta, Fort Mcallister, Fort Wagner S.C, Fort Fisher, N.C., and Richmond (Battery Harrison and Ft Gilmer). Sherman's troops also employed mines around damaged railroad supplies to prevent their salvage during the Atlanta campaign.

117. The Fighting Tanks Since 1916, by Ralph Jones, George Rarey, and Robert Icks, The National Publishing Company, Washington, D.C., 1933, page 262. The British also employed antitank mines. These consisted of lengths of pipe filled with explosives. It worked quite effectively when buried across a road. See FM 20-32 (1976), page 133.

118. Ancient Inventions, by Peter James and Nick Thorpe, Ballantine Books, New York, page 207.

119. Southern Historical Society Papers, Volume X, January to December 1882, Broadfoot Publishing Company, 1990, pages 257-260.

120. Medieval Warfare, by Terrence Wise, Hastings House Publishers, New York, 1976, pages 168-169.

121. OP CIT, The History of Fortification, pages 99-100.

122. "Mine and Countermine in Recent History, 1914-1970," by Russel Stolfi, BRL Report 1582, Ballistic Research Laboratories, Aberdeen Proving Grounds, Maryland, April 1972, page 91.

123. Vanguard of Victory, The 79th Armored Division, by David Fletcher, Her Majesty's Stationery Office, London, 1984.

124. OP CIT, The Genius of China, page 237.

125. OP CIT, Engineers of Independence, page 185.

126. OP CIT, Infernal Machines, The Story of Confederate Submarine and Mine Warfare, page 4.

127. OP CIT, TC 5-31, pages 4-14 and 4-15.

128. On Air Defense, by James D. Crabtree, Praeger, Westport, Connecticut, 1994, pages 183-184.

129. OP CIT, Jane's Military Vehicles and Logistics, 1991-1992, page 198 and "Anti-Helicopter Mine" Brochure, Ferranti Inter., undated.

130. The Russians have even developed formulas for calculating the casualty causing potential of a given minefield. See Soviet Engineer Operations, Special Text, US Army Engineer School, Ft Leonard Wood, Missouri, 5 January 1990, pages 3-5 to 3-7.

131. "The 3d Marines in Desert Storm," by John Admire, U.S. Marines in the Persian Gulf, 1990-1991: Anthology and Annotated Bibliography, compiled by Charles Melson, Evelyn Englander, and David Dawson, History and Museums Division, Headquarters, USMC, Washington, D.C., 1992, page 168.

132. "Defeating the Enemy's Will: The Psychological Foundations of Maneuver Warfare," by David A. Grossman, contained in Maneuver Warfare Anthology, edited by Richard Hooker, Presidio Press, 1993, pages 142-190.

133. War as I Knew It, By George Patton, Pyramid Books, New York, 1972 edition, page 350.

134. Numbers, Predictions, & War, by T. N. Dupuy, Bobs-Merrill Co. Inc., New York, 1979, page 215.

135. The Campaigns of Napoleon, by David Chandler, MacMillan Publishing Company, New York, 1966, pages 149 and 155. For a more recent perspective on the criticality of time in modern warfare, see Fighting by Minutes, by Robert Leonard.

136. Patton's Best, An Informal History of the 4th Armored Division, by Nat Frankel and Larry Smith, The Berkley Publishing Group, New York, 1978, pages 17 and 18.

137. The Rommel Papers, edited by Liddell Hart, Harcourt Brace and Company, New York, 1953, page 300. The original plan called for 25% AP mines. Rommel's engineers were only able to emplace about 14,000 AP mines (3%) of the 500,000 mines emplaced.

138. North Africa, Landmine and Countermine Warfare, 1940-1943, Engineer Agency for Resources Inventories, Washington, D.C., June 1972, pages 103-160.

139. Western Europe, Landmine and Countermine Warfare, 1940-1943, Engineer Agency for Resources Inventories, Washington, D.C., July 1973, page 9.

140. OP CIT, Breaching Fortress Europe, pages 121-189.

141. Citadel, The Battle of Kursk, by Robin Cross, Sarpedon, New York, 1993, pages 164-167. For information on Russian preparations for Kursk, see "Soviet Defensive Tactics at Kursk, July 1943," by David Glantz, CSI Report No. 11, Combat Studies Institute, Ft Leavenworth, Kansas, 1986. Another good account of German engineer operations at Kursk is contained in "If You Don't Like This, You May Resign And Go Home: Commanders' considerations In Assaulting A Fortified Position," by Michael Woodgerd, AD-A244-373, Naval Post Graduate School, Monterey, California, pages 52-82.

142. On War, by Carl Von Clausewitz, translated by Michael Howard and Peter Paret, Princeton University Press, Princeton, New Jersey, 1976 edition, page 75.

143. This data is based on the frequency for which a given mine was mentioned in Hidden Killers, The Global Problem with Uncleared Landmines, Department of State Publication 10098, July 1993. Admittedly, not very scientific, but this is the most comprehensive data available.

144. The New York Times gave the following figures for mines presently emplaced around the world: L-9 Barmine, 6 million, Kuwait, Iraq; VS-2.2, 10 million, Afghanistan, Iraq, Iran, Kuwait; PT-Mi-Ba-III, 11 million, Iran, Iraq, Kuwait, Mozambique, Somalia; Type 72A, 20 million, Afghanistan, Angola, Cambodia, Iraq, Mozambique, Somalia, Thailand, Kuwait; M-18, 6 million, Angola, Mozambique, Central/South America; POMZ-2, 16 million, worldwide; PMN, 20 million, worldwide; PRB 409, 11 million, Afghanistan, Iraq, Iran, Mozambique, Somalia, Lebanon; "New York Times Magazine," January 1994.

The Proliferation of the Mine Threat and the PRORYV System

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The use of mines as an essential part of arsenals around the world is expanding. A bewildering array of mine types floods world arms markets these days. Countries without the means to directly engage the armed forces of the US and its allies recognize that the use of mines is a most efficient and effective means of limiting our mobility of forces. In order to retain our mobility and preserve our mission capability in spite of the rapid proliferation of mines, we must continually develop mine countermeasures systems which are responsive to the widening threat. Finally, when a conflict is ended, the battlespace is likely to be littered by mines. Some naval mines will sterilize (self-destruct) when their timers run out or their batteries die. Naval contact mines and land mines rarely have any mechanism for sterilization. These mines pollute lines-of-communication years beyond a conflict.

Since the industrial revolution, land and sea forces have made great strides in developing weapon systems and tactics that allow higher and higher levels mobility and flexibility. The US has made massive capital investments to make forces that are extremely mobile and flexible. Mobility and flexibility give the armed forces of the US the ability to project massive amounts of fire power around the world, within a matter of days. It is essential, therefore, for countries attempting to act contrary to the interests of the US and its allies to be able to limit the mobility and flexibility of our forces. A significant response to these increases in mobility and flexibility has been the proliferation of countermobility technology, primarily mines.

Mine manufacturers build mine types based on the features of their desired targets. Fusing, warhead size and method of employment are all in response to the target. There are four basic targets for mines:

- Personnel,
- **Tanks,**
- Naval Boats and Craft, and
- **Naval Ships.**

Killing targets outright is not necessarily the intent of the miner. Rather, miners nominally use their weapons to inhibit movement by presenting a credible threat to the combat efficiency of the target. This philosophy of use has evolved from the concept of mass barrage mining. Defending forces will place a mass barrage of mines across the extent of the front that enemy forces could exploit. Mines designed to kill their targets outright are considerably larger than the sort that cause minimum effective damage. The larger mines require more logistics support, more laying personnel and more time to lay than smaller mines. Since the goal is area coverage to reduce mobility, the smaller mines placed at higher rates are preferable. This concept has resulted in mines that are smaller, lighter and easier to use than their W.W.II counterparts. The smaller mines are also cheaper and used more freely.

In addition to mines that users can deliver easier and faster, Current mine technology has also provided mines that are more resistant to countermeasures. Mine manufacturers have accomplished this by technologies ranging from the use of materials resistant to current detection means, to the use of microprocessors to achieve better target discrimination. Ironically, as mines become a more complex problem for mine countermeasures assets, they are becoming easier to prepare and deploy requiring very little specialized training for personnel trained in ordnance handling.

The mine-proliferation problem is not an abstract one based on some future conflict. It is a real problem that currently faces us right now. Antipersonnel (AP) and antitank (AT) mines sell for pennies apiece. The International Red Cross (IRC) and UNICEF estimate that there today there are about 110 million AP mines on the ground. Additionally, mines cause injury or death for over 70 people every day. According the IRC, there are 14 countries that have enough mines on the ground to present a serious threat to the civilian population.

Naval mines sell for between $1,000 and $2,000,000 depending on the complexity and size of the system. Mines ranging from simple contact mines to complex "rising" mines are available on world markets. These mines potentially present a grave risk to naval assets. In terms of naval mines, since the end of WW II, the world has seen at least seven major mining incidents. The US Navy has had a total of seventeen ships damaged due to weapons other than guns. Of the seventeen ships damaged, mines damaged fourteen ships. All of the damage was extensive. Some damage was (like the USS WARRINGTON with 35 dead) tragic. In that same time frame, mines have struck at least 25 noncombatant ships.

There are at least 24 mine exporters in the world; and an uncounted number of countries have acquired the technology base required to produce their own mines. The size of mine systems makes them easy to move and extremely difficult to detect before the first firing occurs in a mine field. As the proliferation of mines expands and the number of producer nations increases, the knowledge-base of the US MCM forces lags further and further behind. To be able to respond to the mine proliferation problem, MCM systems must be robust enough to anticipate as yet unconfirmed mine technologies. Mine proliferation requires an ever-expanding effort at acquiring and exploiting the mine systems. Mine acquisition and exploitation are the only means by which we can determine true mine performance values and develop the tactics and methods to counter those systems. The ability to counter mines may be critical to our ability to operate our forces during conflicts and protect civilian lives after the conflict.

MCM System: The MCM system described has been referred to as PRORYV.

Concept: The PRORYV is designed to be a self-contained, portable system for installation on board landing craft. It is designed to clear a 40m x 200m lane in 40 seconds with the craft maintaining a 10 knot speed of advance. The system consists of a target-designating laser, fire-control system, launchers, ahead-thrown ordnance and lane markers.

The system has a footprint of 5m x 10m and weighs about 20t. The launchers consist of centered stabilization rail and four rockets in a cluster. A laser designator (of unknown type and frequency) is used to designate the lane. The fire-control system commences fire based on two measurements. The first measurement used is the relative position of the launch platform behind the target lane. The second measurement is that the craft is in a horizontal position and pointed toward the target. The fire-control system fires front to rear. Using a speed of advance of 10 knots, the system fires a row of weapons at the target at a rate of 1 per second.

The launchers are set at 45 degree angles and are in fixed positions to provide a 40m-wide spread of weapons. The claimed 3-sigma accuracy of the launch system is plus or minus 1m in waves of 1.5m or less.

The ordnance is a rocket which is electrically ignited and uses a powder propellant. The rocket is 1m in length and carries a 35kg warhead. The explosive portion of the warhead is 25kg of enhanced explosive with a TNT equivalent of 1.6 (40kg or 88 lb. of TNT). Fusing of the warheads is accomplished by an inertial switch and a pair of timers. When the rocket is fired, a 5-second timer begins to run. The 5-second timer is a sterilization or fail-safe timer. When the warhead contacts the water surface or land, a second timer starts to fire the warhead when it falls 2.5m. Should the inertial switch or the second timer fail, the 5-second timer will fire the warhead. The claimed minimum kill radius for the warhead is 5m. A 5m kill radius has been verified against TM-46 series A/T mines and L'DINA bottom influence mines.

Other factors: According to the Deputy Director, the fire-control system and ordnance are adaptations of the very mature ASW systems currently produced and under development. During a visit to MODI, the deputy director of MODI asked the Director of the development lab if the fact that the system has been developed to operate from the Russian conventional landing craft would impact development of an LCAC-based system. The Director replied that it would not because the system was designed to be autonomous from the host platform, the LCAC has plenty of space and weight capacity, and that the LCAC would probably be more stable than the landing craft as a launch platform.

A further conversation between the Director and Deputy Director of the Lab revealed that their main placement error for the system would likely not be as a result of the sea state or other environmental factors. Rather, it would be caused by the steering error of the Coxswain.

At the presentation of the DET/SABRE system at MODI, the Deputy Director and a lead scientist at the lab began a conversation of their review of DET-like and SABRE-like systems. There was a great deal of noise in the room so that comprehension of the conversation was fragmentary. However, the lead scientist indicated that the net-system has been too heavy (mentioned the number of 3t) and that it had been impossible to control the linear charge with sufficient accuracy. Therefore they had decided to use individual weapons in the configuration shown to us.

SESSION ON THE LITTORAL ENVIRONMENT
MONTEREY BAY AQUARIUM

The physical and biological environments are dominating factors in the harnessing of technology to deal with the "Mine Problem" -- including the offensive/defensive use of mines for our own purposes. The Symposium took advantage of the proximity of the Naval Postgraduate School to the Monterey Bay Aquarium to raise the awareness of participants about the complexity of the littoral environment.

There were three components to this Session. At the beginning were the formal presentations by the Oceanographer of the Navy, RADM Paul E. Tobin, USN, and by members of a specially constituted Very Shallow Water Mine Countermeasures Unit led by Capt. Thomas R. Bernitt, USN, Commander of Explosive Ordnance Disposal (EOD) Group One. Bernitt's team consists of specially trained EOD, Navy Special Warfare (SEAL), and Marine Corps Combat Reconnaissance specialists. Among other duties, this group has operational cognizance over the marine mammals used in Mine Countermeasures. Admiral Tobin's paper and the briefing by Capt. Bernitt and his colleagues are reproduced here.

Oceanography is a combat support discipline, and the revolution in oceanographic technology is paced by the increasing use of remote sensing -- oceanographic measurements from space! Advances in other enabling technologies are and will continue to be based on the increasing use of the Global Positioning System, or GPS (its very precise models), to allow one to discriminate among nearby locations. There will be a revolution in the nature of oceanographic products, including tactical decision aids, resulting from these modern technologies.

The initiative by the Navy's Mine Warfare Command to establish a Very Shallow Water Mine Countermeasures Unit that includes Marine Mammals (dolphins) is another example of "combat oceanography." Capt. Bernitt and his associates described their program, in which they have begun to explore the operational aspects of VSW MCM with an emphasis on being able to conduct clandestine reconnaissance of Amphibious Objective Areas (AOAs). They intend to be able to map the locations of mines and obstacles, and also want to establish the nature of the bottom in terms of trafficability for tracked amphibious vehicles.

These speakers emphasized the nature of the VSW MCM environments. Even a seemingly calm water surface can mask current and tidal surges, and those surges can involuntarily move a swimmer as much as twelve feet. A swimmer immersed in such a water environment cannot control his movements. In addition, there are difficult conditions of visibility, variations in the nature of sea life and sea growth, and the possible use of "stealth" shapes for mines.

The exhibits at the Monterey Bay Aquarium served to show attendees just what a kelp forest looks like, and what some of the underwater habitats can contain. Also, one must look at sea life as potential false, non-mine targets for acoustic underwater detection devices.

This event provided graphic illustrations of the very real, operational problem facing mine hunting and mine reconnaissance -- finding the desired target in the presence of a great many false targets. The problem is further exacerbated by mine burial, which can occur by the action of currents and tidal surges.

The formal presentations concluded with a brief introduction of the capabilities of the marine mammal systems. These dolphins have shown themselves to be remarkable, and still the most sensitive, tools for finding and classifying sea mines -- including buried sea mines. (As a parenthetical note, it is significant that the best landmine detection systems are also biological systems -- dogs and pigs. Reserach interest in just how these land mammals are able to detect mines is growing. There are those who believe that the odor sensing capabilities of animals contain the key to mine detection, both on land and at sea.

At the conclusion of the formal presentations, attendees visited some mine-related technology displays provided by our Corporate Sponsors for this Session, and also visited the various tanks at the Aquarium containing living examples of just what the littoral environment is like. Symposium organizers believe that the images of the flora and fauna of the littoral environments, together with the descriptive narration of the problems of Mine Countermeasures in Shallow Water, will be of great utility to researchers as they search for technological answers to the Mine Problem.

This unstructured period also provided a relaxed opportunity for attendees to discuss what they had heard from our distinguished speakers earlier in the day, and to interact with those speakers and other senior personages who were present.

THE RELATIVE CURRENT CAPABILITIES OF TECHNOLOGY AS COMPARED WITH MAMMAL SYSTEMS FOR BOTH SEAMINE AND LANDMINE DETECTION

The most humbling lesson of the Symposium was that, despite real and significant technological strides, porpoises (dolphins) remain by far the most effective and fastest detectors of seamines, especially buried ones, to date; and dogs remain by far the most effective detectors of landmines. A recent scientific report stated that the dog's nose/olfactory system is a *million* times more sensitive than that of the human's. In South Africa, where trained dogs have long been used for landmine detection, they have the highest success rate -- over 90 percent -- of any method yet tested, and dogs were successfully, and safely, used for mine detection operations in Bosnia. Similarly, a trained dolphin is able to use echolocation/identification (acoustic sensors) to distinguish between otherwise identical metalic mine-like objects whose only difference is a fraction of an inch in thickness; can differentiate size, structure, shape and material composition of submerged objects at incredible distances; and can complete a seamine search of a 2-square-kilometer area of ocean in only 4 hours, compared to 14 hours by a dedicated Navy vessel going at 3 kts. Indeed, the porpoise consistently outperforms any available artificial system, especially in poor acoustic environments, in high-clutter areas, and where objects are buried beneath the ocean bottom -- all cases where detection capability is often the most needed. These highly intelligent sea mammals can also be used to develop systems which work in shallow water/surf zones -- by reverse engineering the dolphin's sensory capabilities, future AUV systems may be designed and built which begin to match their natural capabilities. Clearly, we still have much to learn from humankind's two "best friends."

Developments in Rapid Environmental Assessment

RADM Paul E. Tobin, USN
Oceanographer of the Navy

It is a pleasure to be back in Monterey, and I cannot think of a better setting than the Monterey Bay Aquarium to discuss matters relating to oceanography. I appreciate Dr. Bottoms invitation to speak tonight, for I think it is very important that the linkage between mine warfare and oceanography be clearly established.

We certainly have an impressive representation from the mine warfare community with four Mine Warfare Commanders in attendance. Admirals Horne, Mathis, Pearson and Conley represent over ten years of command experience and have played a key role in keeping Mine Warfare high on the Navy's agenda. We are also fortunate to have RADM Rick Williams, the Mine Warfare PEO, with us and I was glad to hear he will be working in N85 on the CNO's staff in the coming months. Some may have seen the name Tobin and thought yet another former Mine Warfare commander was here. Alas, I am the other Tobin --- RADM Jake Tobin has recently retired and is living in the Norfolk area.

I do not presume to be an expert on mine warfare, but like almost all naval officers, I have had many experiences that have been affected by the use or threatened use of mines. In my current assignment as Oceanographer of the Navy, I have been emphasizing closer ties to the tactical commander and the operating forces. Rapid Environmental Assessment is one of our highest priorities, and the Mine Warfare threat is always an important part of any assessment. This is particularly true in the littoral.

My involvement with Mine Warfare started in Vietnam in 1971 and 1972, where we lived with the threat in the rivers and the deltas and in late 1972 undertook our last major offensive mining operation in Haiphong. While I was Commanding Officer of SWOS, I developed a strong relationship with the USS SAMUEL B. ROBERTS and spent several days at sea with Captain Paul Rinn and his fine crew. Obviously we viewed the subsequent mining of the S. B. ROBERTS in the Gulf with great concern and interest. While in Subic Bay as Commander Task Force 75, I developed a similar relationship with Captain Ted Hontz of the USS PRINCETON and saw first hand the major damage caused by a mine to that great ship. In that same job I oversaw the operation of the Mobile Mine

Assembly Groups in the western Pacific and learned a great deal about our offensive capabilities and the very talented specialists who work in that field. We also had the opportunity to host the Japanese Self Defense Force Mine Warfare squadron that was the first Japanese Naval Force to deploy from home waters. In this case they were on their way to make a contribution to the Gulf War. It is interesting that this particular force was chosen to introduce a new dimension to Japanese Maritime Self Defense Force operations. Finally, in my last assignment with the Chief of Naval Education and Training, I worked closely with the Mine Warfare Training Group in the planning and execution of the move from Charleston to Engleside. I have not yet had the opportunity to see the new facilities but hope to visit RADM Conley early next year.

The impacts of Mine Warfare in World War I, World War II, Korea, Vietnam, and now the Gulf War are well documented. Mines continue to be a low cost, very effective way to drastically slow a show, if not stop it. Weapons that can be effectively delivered by a range of platforms from rowboats to ballistic missiles pose a very real threat, and unfortunately, this technology is accessible to almost any nation.

A big part of my business is to know the ocean bottom. Such knowledge is obviously very important to the mine layer and the mine hunter. It really comes down to characterization and the development of an accessible and accurate data base. We do essentially the same thing in Astronomy, where we are painstakingly digitizing the observations of the last 75 years and putting the data into a form that can quickly be compared with current observations. We do the same thing for weather climatology, where trends and deviations are important clues to the future.

The following kinds of data are critically important to us in littoral: wave characteristics and sea state, surf conditions, bottom topography and composition, navigational hazards, biological phenomena, such as noise and luminescence, water turbidity, salinity, tides and currents. These factors all play a role in the mine hunting equation.

Oceanography has come a long way in solving this data base problems. From man's first ability to calculate latitude by the Greek Pytheas, who ventured as far north as Iceland in 325 BC, to the voyages of Captain Cook in 1768 that used the Harrison chronometer and accurately calculated longitude. In 1872 the voyages of H.M.S. CHALLENGER established modern oceanographic science with detailed collection of water column data and bottom samples around the globe. The explorations of GLOMAR CHALLENGER in 1968-1983 yielded detailed core samples from the ocean sediments and a clearer picture of the ocean bottom topography. Side scan sonars, multi-beam swath bathymetry and now perhaps, the most dramatic improvement of all, the Global Positioning System, have finally allowed us to obtain a view of the ocean bottom.

Bob Ballard states the issue well in noting that when Neil Armstrong set foot on the moon we had yet to discover the true extent of the largest geographical feature of our own planet -- the mid Atlantic ridge. In fact, the first real global representation of the ocean floor developed by Bruce Heezen and Marie Tharp at the Lamont Doherty Geophysical Laboratory were not published until 1972.

This brings us back to the all important matter of defining the ocean floor data base in the littoral as a key factor in mine warfare. With the new tools I have described, we can survey the ocean bottom and construct computer generated images on the fly and make analyses in real time with precise navigational accuracy. How are we doing? Even though the demise of the cold war was provided us with unprecedented access to the world's littoral waters, we still have a survey backlog of some 360 survey ship years. Further, as RADM Williams often reminds me, our pictures are not quite accurate enough. We really need to know whether that new metal object is a refrigerator, an abandoned car, or an influence mine. The tools to make these determinations may soon be at hand, but presently we still have a need for time consuming swimmer or ROV searches.

GPS accuracy to less than 1 centimeter is possible today, and new bottom scanning technology coupled with sophisticated data base comparison software will dramatically speed the survey process. Airborne LASER Bathymetry is a new fast way to acquire clear water gross survey data in very short periods of time. Will we ever have a clear picture of the bottom and slightly below? It is not a question of if, but rather of when, and this will depend on the seriousness of our commitment. Unfortunately, today we are the last remaining nation to be mounting a world wide survey effort. Our eight ship fleet will be sorely taxed to gather the data that technology and world politics are making available.

Conferences such as this, coupled with new partnership initiatives, like the National Oceanographic Partnership Act and active support of Oceanography education programs, will move us in the right direction. Public awareness of the challenges of Oceanography, our last great frontier on earth, is growing, but the U.S. Navy's interest has and will continue to be long-standing. It is a core competency of our profession and can make the difference between victory and defeat in modern warfare. I assure you that the Oceanographer's office will continue to work closely with the mine warfare community in what is very clearly in both of our best interests. I appreciated the opportunity to be with you tonight and look forward to our mutual challenges ahead.

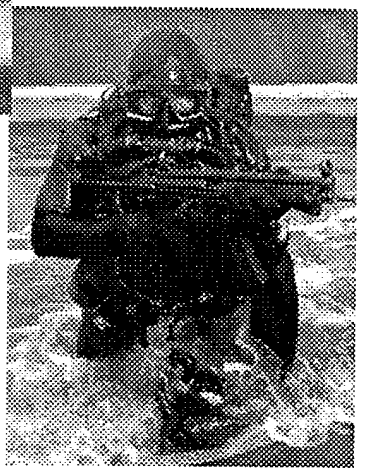
Developments in the Very Shallow Water-Mine Countermeasures Test Detachment Program

CAPT Thomas R. Bernitt, USN
Commander,
Explosive Ordnance Disposal Group One

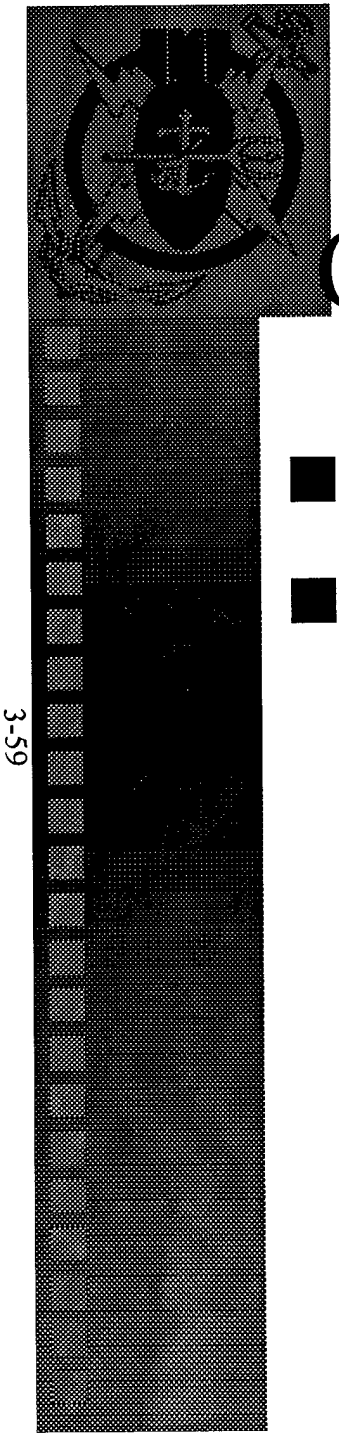
Very Shallow Water-Mine Countermeasures Test Det





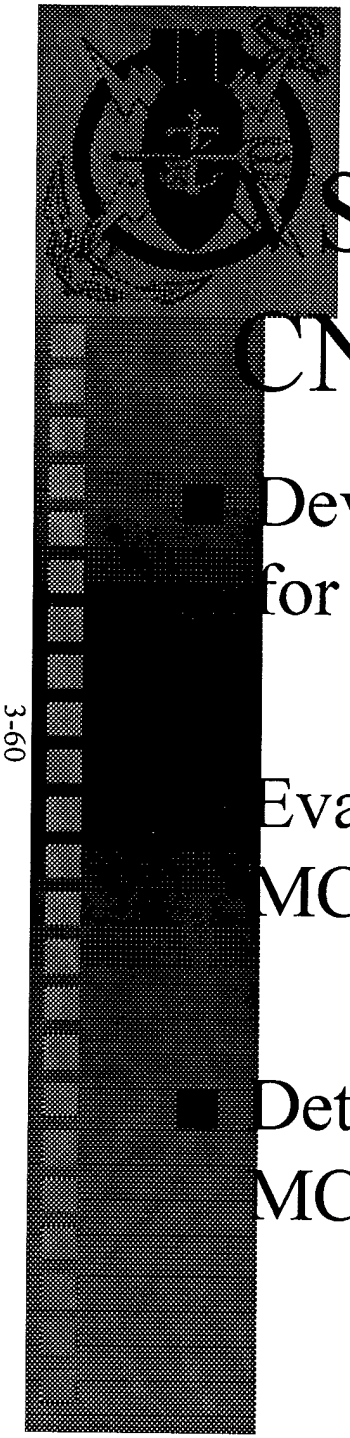


- Navy SEALs
- Navy EOD
- USMC Recon



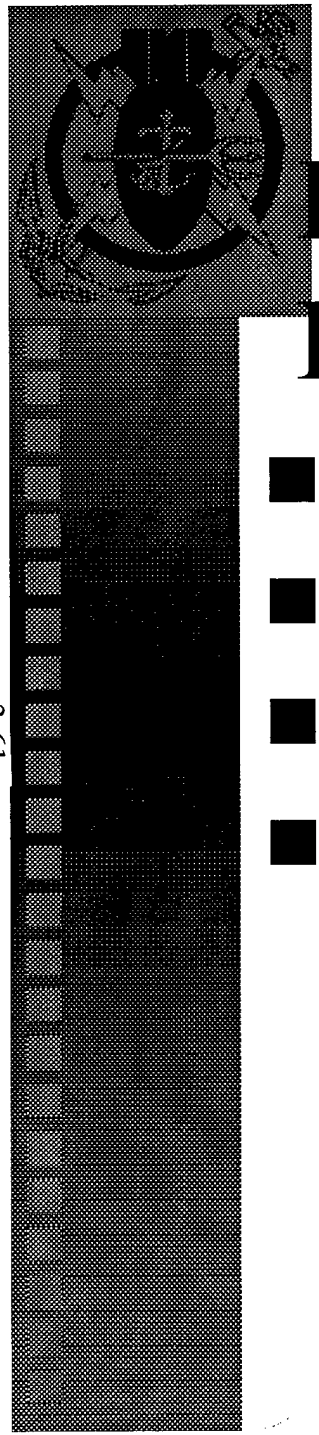
Outline

- Conops
- Progress



VSW MCM Test Detachment CNO Objectives

- Develop tactics, techniques & procedures (TT&P) for mine/obstacle reconnaissance.
- Evaluate prototype equipment to optimize VSW MCM capabilities.
- Determine requirements for sustaining VSW MCM capabilities.

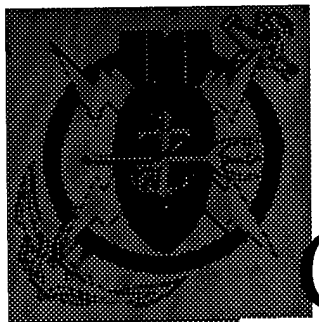


Issues to be Resolved at a Later Date

- Insertion/Extraction
- Communications
- Escape and Recovery
- Neutralization

Chain of Command

ADCON = COMEODGRU ONE
OPCON = COMINEWARCOM
CATF



Current Manning

10 EOD Personnel

(1 officer/9 enlisted)

8 Naval Special Warfare

(2 officers/6 enlisted)

7 USMC Recon

(1 officer/6 enlisted)

1 HMC DMT (8494)

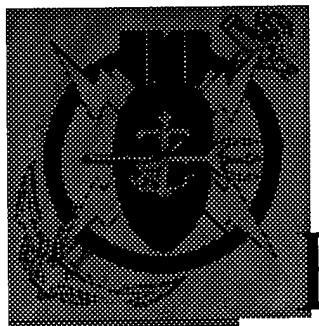
Concept of Operational Employment
(VSW MCM Forces)

MISSION - TO ENABLE AMPHIBIOUS OPERATIONS BY PROVIDING MINE AND OBSTACLE RECONNAISSANCE NEUTRALIZATION CAPABILITIES IN THE VSW ZONE (40′ to 10′).

Two Tasks:

I. **Advance Force mine/obstacle reconnaissance in the VSW zone**
   - *Examination of potential sites*
   - *Establish boat/swimmer lanes through the VSW zone for other forces*

II. **Pre-assault lane reconnaissance for mines/obstacles in VSW zone**
   - *Locate, identify & report mines/obstacles in VSW lanes*
   - *Evaluate alternative VSW lanes selected for assault*
   - *Prepare to neutralize mines & obstacles*

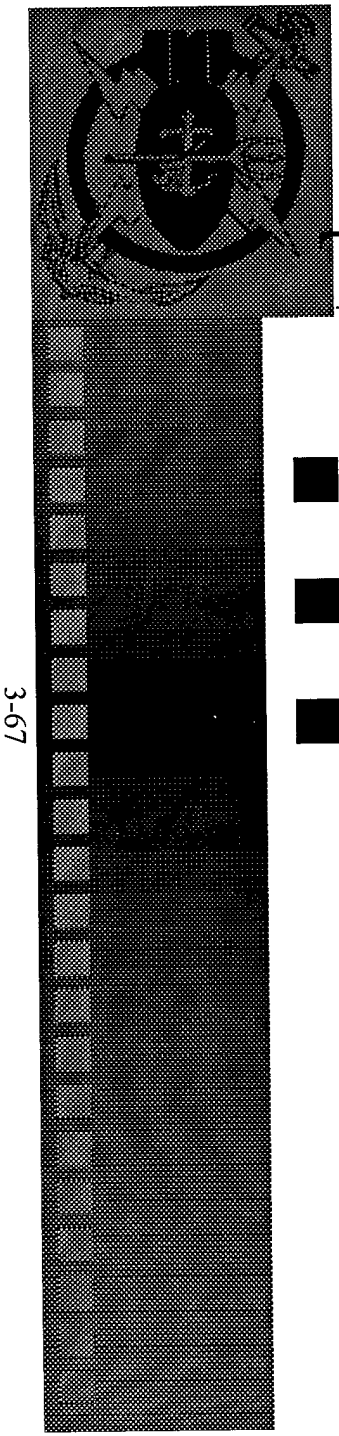


Equipment

- UBA
  - Draeger Extreme
  - S24
  - Draeger LAR V
  - SIVA 55
- Navigation
  - SINS (SEAL Inshore Navigation System)
  - MUGR GPS

Equipment

- SONAR
  - AN PQS-2A
  - DIPS (Diver Information Processing System)
  - Visual Display for 2A
  - ARL Visual Display Sonar

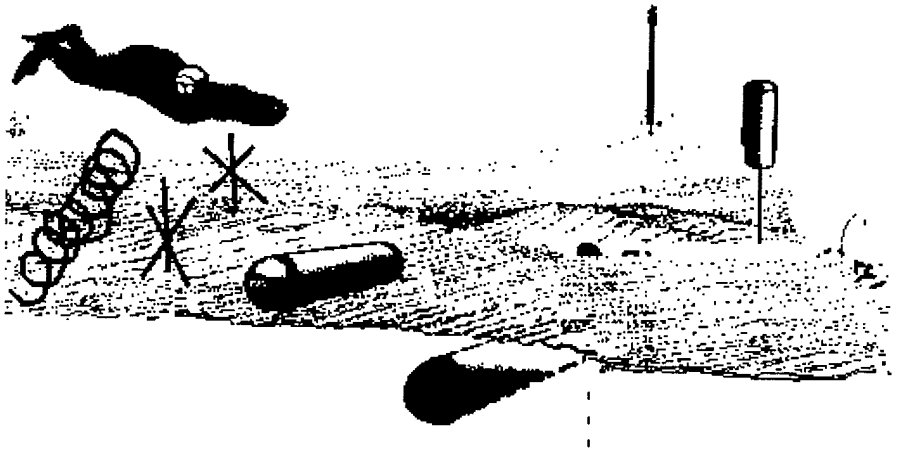


Tactical Concepts of Operation

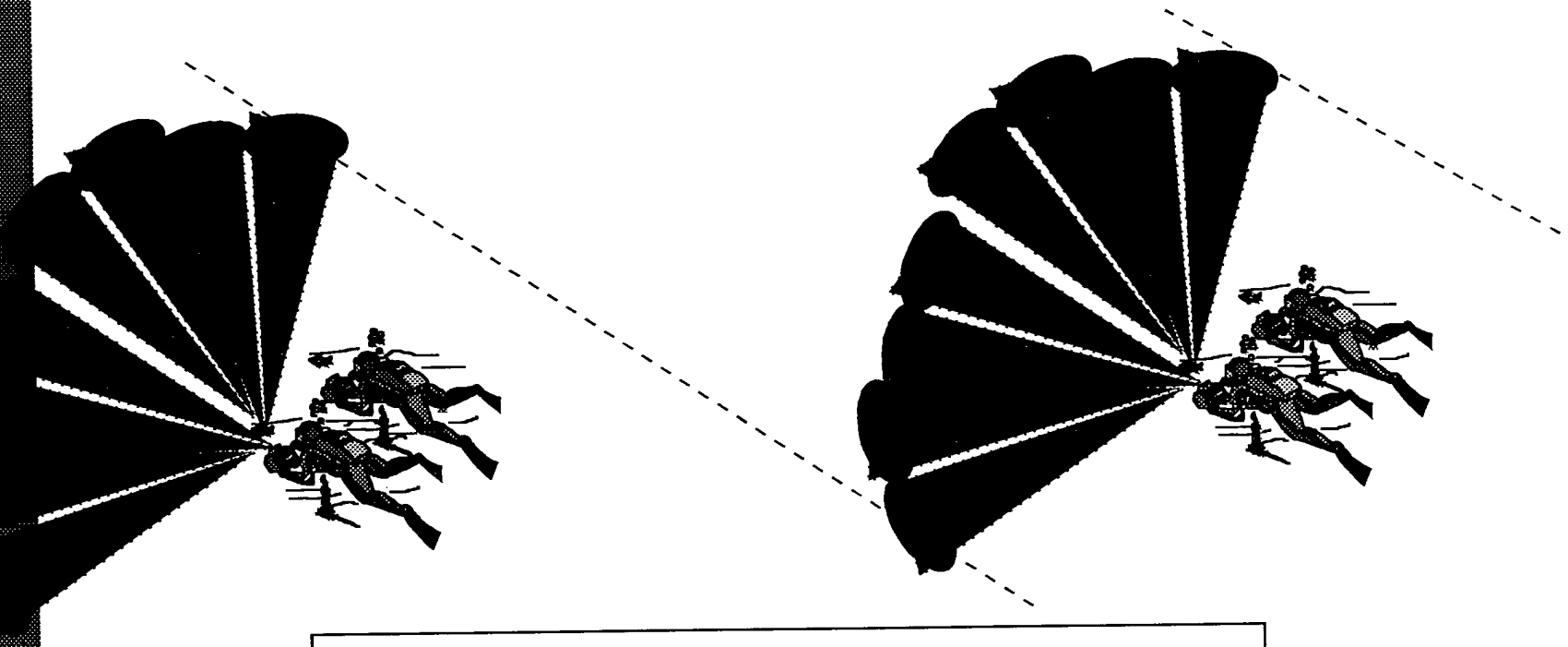
- "Diver Only"
- "Mammal System Only"
- Integrated Diver and Mammals

Diver Concept of Operation

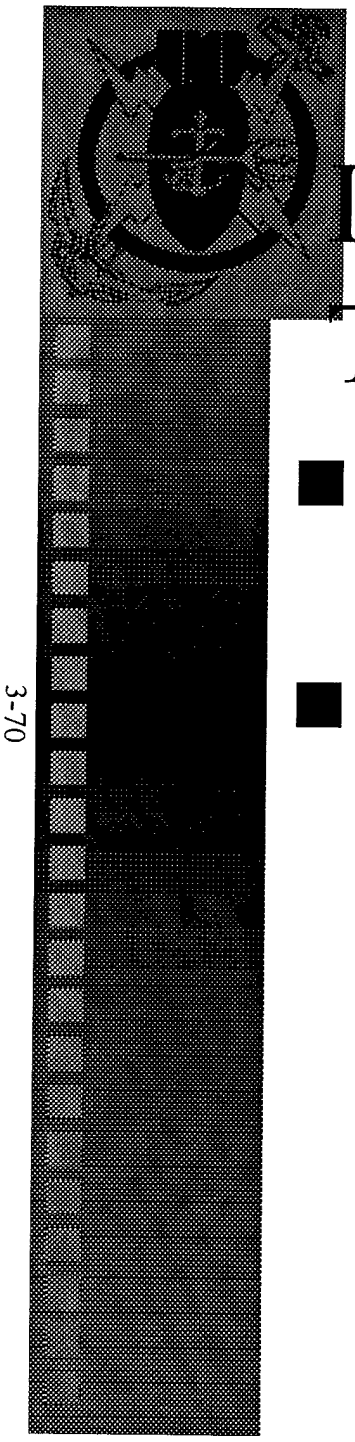
- **Insert OTH**
  - Use of DPD's (Diver Propulsion Devices)
- Divide into two swimmer groups
- Reset master and slave
- Swim overlapping lanes
- Exfil to master and slave
- Extract



Diver Tactics



Diver pairs , SINS and AN-PQS 2A
Stop to scan 15 yds
Prosecute tgts, return to lane and continue

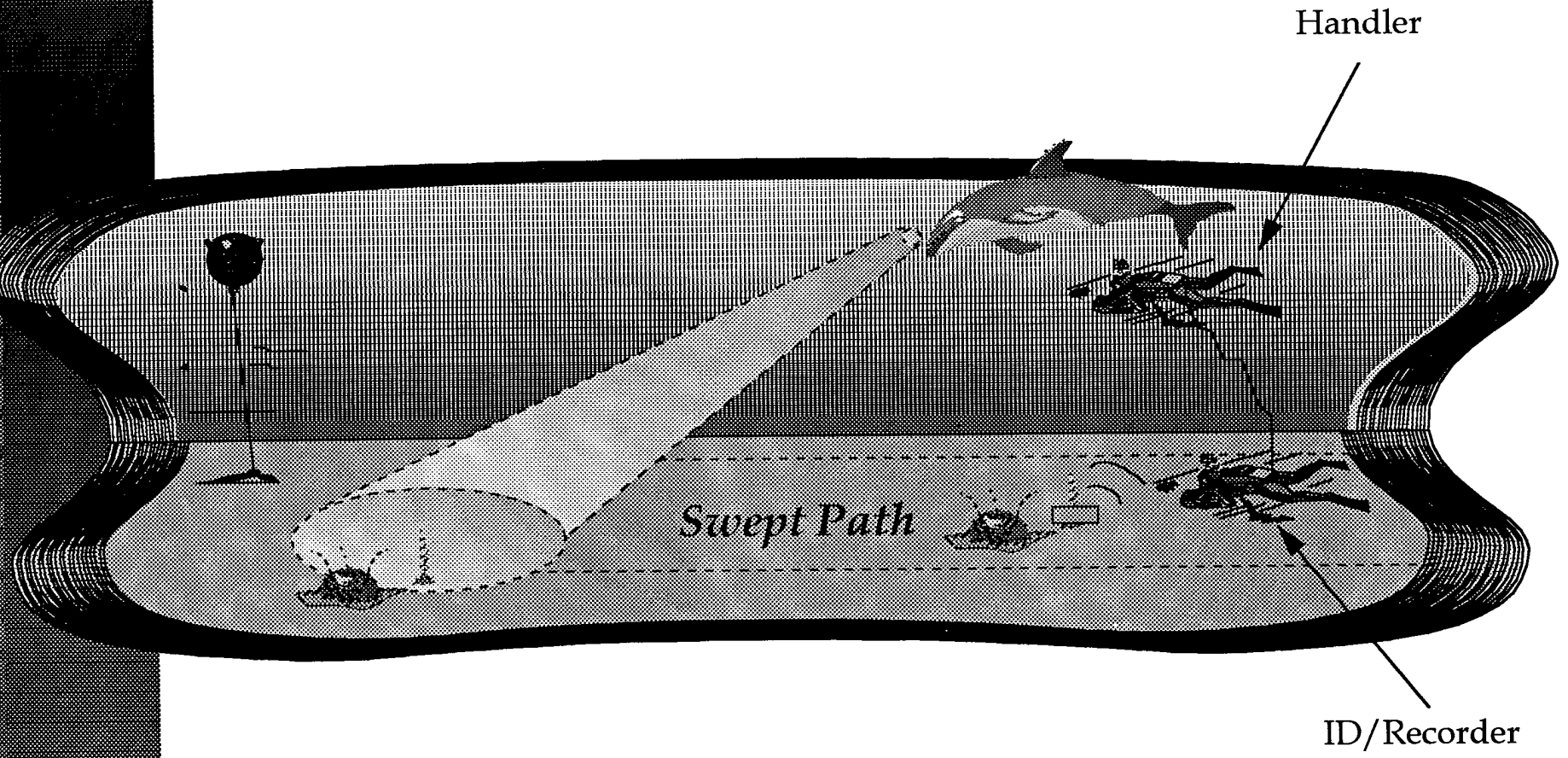


Integrated Diver/Mammal Tactics

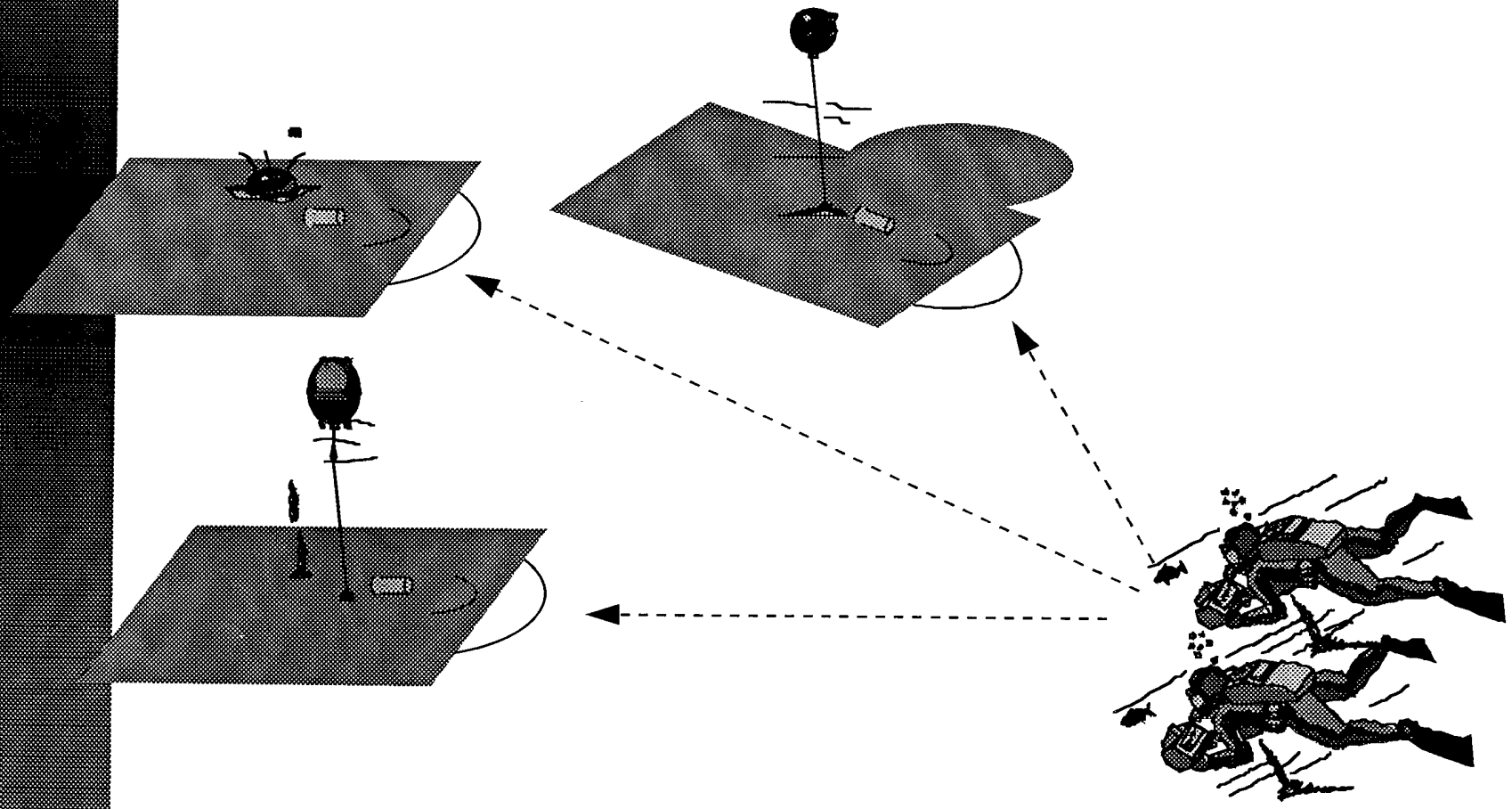
- Mammal system(s) will sweep field during darkness, marking suspected targets
- At first light, divers will reacquire pingers, identify and possibly neutralize targets

Visual Representation of Future Mammal Tactics

subsurface capability with DPD)



Integrated Diver/Mammal Concept (Diver Reaquisition)



VSW Test Detachment Progress

Jan 96 CNO approves 1 yr.. test (EOD/NSW/RECON)

Feb 96 PMS-EOD develops hardware program

EOD/NSW divers begin baseline training

Examine feasibility of MMS alternatives

Mar 96 UBA prototype tests begin (at NEDU)

Low-profile MMS prototype craft evals

Apr 96 Divers integrate SINS into tactics

Apr/May USMC Recon report/begin base training.

– **Test Det Fully Manned**

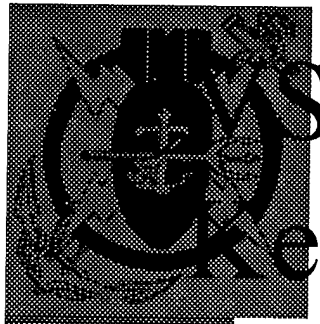
May 96 Reprogrammed FY96 $ approved

VSW Test Detachment Progress

- **July 96** Test det moved into interim facility
- Aug 96 Exercise JTFX 96-2
- Sept 96 Extension Letter Promulgated (Oct 97)
  UBA decision made (Draeger Extreme)
- Nov 96 Requirements Meeting
  Exercise Dugong, Australia

Exercise Schedule

■ RIMPAC 96	May 96
■ JTFX 96-2	Aug 96
■ Dugong 96	Nov 96
■ Kernel Blitz 97-3	June 97



VSW Test Detachment Key Events Ahead

Requirements Defined	- APR 97
(unit configuration, force requirements, equipment, homeport(s))	
Exercise Kernel Blitz 97	**- JUN 97**
Establishment Decision Made	**- JUL 97**
VSW MCM Unit established	- OCT 97
IOC Diver System (estimated)	- OCT 99
IOC Mammal System (estimated)	- OCT 00
FOC VSW MCM Unit (estimated)	- OCT 02

CHAPTER 4: LANDMINES AND HUMANITARIAN DEMINING

This Chapter presents material on the problem of proliferation of landmine technology, the elements of the debate on the proposed ban or restriction of the use of landmines, and some of the technological approaches to meeting the difficult demands of Humanitarian Demining.

HUMANITARIAN DEMINING

Collected for this Chapter are the papers and letters that the authors, themselves, felt were most appropriate to the Humanitarian Demining application. The reader is cautioned that technology applications discussed under Humanitarian Demining may, in fact, also have utility in military operational scenarios of countering mines on land or at sea.

It is useful to keep in mind the operational distinctions between Humanitarian Demining and the military scenarios:

* Technologies (and systems) destined for the humanitarian demining applications should be readily obtainable and capable of being operated by personnel indigenous to the areas in which the demining operations will be conducted. In general, such personnel will not be used to dealing with complex tools and instruments. Ease in instructing such personnel in both training and maintenance is therefore as important a consideration as are the costs (financial and personnel) associated with acquisition, staffing and maintenance. Please see below for additional comments regarding cost.

* Systems and approaches developed for the Humanitarian Demining applications will not, in general, be used to conduct operations under fire or under the tight time constraints imposed by military land and sea operations. Thus, in humanitarian demining, the user has the luxury of picking the time of day and the weather conditions most conducive to success of the operation.

* The objective of humanitarian demining operations is to return to the indigenous peoples land that has been mine infested. The need is for the people to have confidence that they may use the land for agriculture or for any other purpose without fear of continuing to receive the casualties that are now occurring. In practical terms, providing this kind of assurance about safe use of an area is a very difficult thing to do. In many parts of the world, economic necessity to farm, fish or to gather fuel acts to increase the willingness of indigenous peoples to expose themselves to the risks of mine injuries.

A comment on cost. It appears that this whole subject of cost associated with humanitarian demining approaches needs further discussion. While it is possibly relevant that the choice between or amongst two or more approaches that promise the same operational capability can be influenced by cost, that is not the situation that normally occurs. Instead, the choice may be between laboriously crawling over the entire contaminated area using sticks as probes, versus the use of a million-dollar

bulldozer that can rapidly, and relatively safely, strip and sift the soil to remove landmines.

In the cost equation, it is also necessary to include opportunity costs. What are the true costs associated with the continuing denial of productive farmlands or other areas of commerce and economic viability? There has been a tendency to use such figures as $1,000 per mine recovered without considering the alternatives. This is an example of what economists call "harmful sub-optimization."

The importance of economic measures of effectiveness is so great that the 1998 Symposium on Technology and the Mine Problem will include this subject in its call for papers.

The Hon. H. Allen Holmes, Assistant Secretary of Defense for Special Operations and Low Intensity Conflict (SOLIC), led off the subject of Humanitarian Demining with his luncheon address Tuesday Nov. 19, on the history and direction of U.S. government policy in this critical area. Following Ambassador Holmes' address, the first plenary session established and delimited the terms of the debate on important policy aspects of the issue. It also set the tone for subsequent discussions of the more technical demining developmental issues. Session co-chairs focused on the different organizational and cultural challenges which render policy choices and decisions on demining so difficult to make.

Among the three speakers in the plenary session on Humanitarian Demining and Demining Policy there was consensus on the need to effectively meet the humanitarian demining challenge, but views differed when it came to interpreting U.S. administration policy, timing of implementation, and whether its long-range effect would become more restrictive on the U.S. than on its potential enemies. Mr. Steve Goose of Human Rights Watch was particularly effective in arguing that a total ban on the use of anti-personnel landmines, "smart" or dumb, was the defacto outcome of U.S. policy initiatives to counter what he saw as "WMD in slow motion." Arms Control and Disarmament Agency representative Mr. Robert Sherman tended to emphasize incremental progress through the Convention on Conventional Weapons (CCW), whose membership included both Russia and China, each large-scale manufacturers of anti-personnel landmines (APLs) with stocks for resale throughout the globe. And Lt. Gen. Robert Gard, USA (Ret) presented a moving testimony detailing why the time to outlaw anti-personnel landmines is long past. The Open Letter to President Clinton signed by him and fourteen other high-ranking former U.S. military officers attesting to the fact that such a ban is not only humane, but militarily responsible, is reproduced in this Chapter.

Despite differences of opinion by speakers over the relative merits of pursuing mine self-destruction, self-deactivation, or self-neutralization technological approaches, however, the conference as a whole seemed impressed by the gravity of how some form of universal ban on landmines might help alter the grim statistics of 100,000 civilian casualities occuring per year from previously unrestricted use of anti-personnel landmines.

The related plenary Session on Technology and Humanitarian Demining featured four speakers who each detailed specific aspects of the problem in the field and their personal experiences in trying to deal with humanitarian demining challenges in various countries. Major Colin King's slide presentation was utterly compelling in its detail concerning the anti-personnel landmine threat and its

impact worldwide (his paper is in Chapter 3 of this Proceedings). Sam Samuels of Essex Corporation and Lt. Col. Garth Barrett explained their approach to training indigenous demining teams, and the challenge of determining how effectiveness can be measured and proven to peoples of different cultures.

Professor Nicoud reinforced this aspect of the problem through his detailed presentation of the ongoing, massive demining efforts in Cambodia. The differential impact of culture and confidence was vividly portrayed in his example, whereby demining teams would play a game of soccer on the very grounds on which they had recently completed their demining efforts. Richard Walden of Operation USA/Operation Land Mine explained how the new roles of non-governmental organizations (NGOs) and PVOs are presenting challenges for governmental agencies to develop both planning and resource methods to deal with these worldwide problems. His bottom line: We need to know more than we do to effectively work together, but we must, and it will be done.

The final Session in this series, parallel Session XXII on Humanitarian Demining, featured ten speakers who largely provided technical details reinforcing the insights from previous sessions. Scheduled near the end of the conference, it covered new project initiatives, recent Bosnian experiences with the M-60 A-3 turretless tank, a discussion of a new combined sensor package to help discriminate non-mines from mines and largely eliminate the metal detection "clutter" problem, and a presentation on the use of LEXFOAM to rapidly and effectively deal with designated anti-personnel lanemine threats with a minimum of danger to demining teams.

The History and Future of U.S. Policy on a Universal Anti-Personnel Landmine Ban

The Hon. H. Allen Holmes
Assistant Secretary of Defense,
Special Operations and Low Intensity Conflict

Good afternoon. It is a pleasure to be with you this afternoon and to be part of the 1996 Symposium on Technology and the Mine Problem. It gives me a chance to do two of my favorite things – talk about how the U.S. government has responded to the worldwide anti-personnel landmine crisis . . . and get out of the Pentagon.

The anti-personnel landmine crisis has developed principally because of the way the mines have been used over the last 15 years or so – mostly in internal conflicts and predominantly in developing countries. Many landmines have been indiscriminately laid by militaries, paramilitaries and insurgents. In some cases, they have been employed specifically as weapons of terror against the civilian population. The result is a humanitarian problem of epidemic proportions. It's estimated that as many as 100 million anti-personnel landmines are scattered over 60 countries, killing or maiming an estimated 1,200 people per month . . . or one every thirty minutes. Last year, 80,000 mines were removed, but many more were planted. At our current clearing rate of 100,000 anti-personnel landmines per year, it will take over 1,000 years to clear the landmines in the ground today. The countries most severely afflicted by these "hidden killers" are Afghanistan, Angola, Croatia, Iraq, Somalia, Mozambique, Bosnia and Cambodia – where one of every 236 people is an amputee – about the highest rate in the world.

An anti-personnel landmine – a simple $3.00 weapon – doesn't know when conflict ends. And it cannot distinguish between the steps of a soldier and that of a child. Long after a conflict is over and the warring troops have gone, anti-personnel landmines remain . . . often for 30 years or more.

The anti-personnel landmine crisis has taken an enormous toll on populations and governments around the world. And their cost goes far beyond the initial tragic toll in human suffering. The failure of a country to address the proliferation of anti-personnel landmines, beyond the obvious personal suffering, denies farmers use of their fields which stymies the resumption of agricultural production, denies access to markets, reduces public confidence in fledgling new governments and creates many other hurdles for a nation trying to heal the wounds of war.

The exorbitant cost of mine-clearing operations siphons off already scarce funds. Anti-personnel landmines make the reconstruction of rail and road networks, of power lines and of waterways nearly impossible. In Mozambique, where civil war was waged for almost 20 years, over 2 million landmines have been laid by the warring parties. The United Nations reports that all 28 major road systems are blocked by uncleared mines. And because many anti-personnel landmines were designed to maim and not to kill, mine injuries cause tremendous trauma, require extensive medical treatment and follow-on care, and overburden existing health care systems, raising health care costs beyond what developing countries can handle.

Perhaps most tragically, anti-personnel landmines block access to vast stretches of otherwise habitable and usable land. The loss of agricultural land takes away the only means that many of these poor agrarian people have to earn a living. So, beyond the injuries inflicted and the medical expenses incurred, anti-personnel landmine fields drive whole societies into helpless, destitute poverty with no way out. In northern Iraq, for example, children of farmers now harvest anti-personnel landmines from their fields instead of crops. They risk life and limb to sell the scrap metal from a landmine.

Anti-personnel landmines are also a primary impediment to repatriation and reconstruction. The return of refugees is fraught with danger and can be delayed because of anti-personnel landmines. Often, refugees who fled their country during war are forced to remain in a foreign country, dependent on international relief. But when mines don't prevent relief organizations from delivering food and emergency supplies, they make already difficult relief operations more hazardous. If overland transport is too dangerous, air transport must be used – a more costly alternative. This widens the ever-increasing gap between the growing humanitarian needs and the shrinking world capacity to meet these needs.

It is against this backdrop that the extent of the landmine problem became widely understood and the call for a total ban on landmines developed and intensified. Based on what I've told you about the socio-economic costs of mines – not only for afflicted countries but for the entire international community – this might seem the appropriate solution. But the issue is really quite complex. And there are no simple answers because at the present anti-personnel landmines are an integral defensive element in our military doctrine – how we fight war – and even though the U.S. has been responsible in its use of mines, we recognize that we must look for other ways to do our business.

Landmines are important defensive battlefield weapons used to counter enemy mobility, help shape the battlefield, protect exposed flanks from counterattacks, and create defensive positions. Most militaries use minefields tactically as an integral part of many phases of war fighting. In Operation DESERT STORM, for example, the coalition forces used air-delivered mines to protect the right flank of U.S. and British forces while they swung around Iraqi troops in Kuwait. These mines held two Iraqi divisions essentially immobile, preventing their counter-attack on the exposed American/British flank.

Minefields are an inexpensive and vital force multiplier. Used in this manner, mines can successfully defend a small force against a larger attacking force or until reinforcement arrives. Barrier minefields are laid in demilitarized zones and between hostile nations or opposing forces to deter and raise the cost of aggression, to delay enemy forces in the event of attack, and to counter the possibility of surprise, such as in Korea. Landmines save American soldiers' lives by providing critical defensive advantage on the battlefield.

Proponents of an immediate total anti-personnel landmine ban assert that while the mines serve an important military function, this pales against the human tragedy resulting from the use of mines. The leaders of this constituency within the U.S. Congress are Senator Leahy and Congressman Lane Evans. They are joined in their views by such prominent people as former Secretary of State Cyrus Vance and by well-respected organizations like Human Rights Watch and Vietnam Veterans of America Foundation. Internationally, they are supported by such leading figures as the Secretary General of the United Nations and by the President of the International Committee of the Red Cross.

Recognizing the current lack of militarily acceptable alternatives to anti-personnel landmines, policymakers in the U.S. and in many other countries have turned to technology in their search for meaningful solutions. The militaries of most industrialized countries increasingly use sophisticated mines that self-destruct after a certain period of time. Nations developed such devices to protect their troops, which are often required to maneuver over areas where they have laid mines. The commander would know that the mines had self-destructed after, say four hours, and that he could safely permit his troops to traverse the minefield they had earlier laid.

The self-destruct feature ensures that the anti-personnel mine will not only be disabled, but also that it cannot be re-used. The fact that a so-called smart mine is powered by a battery means that a natural back-up feature exists that will ensure self-deactivation of the mine, even if the self-destruct mechanism fails to work. As batteries deplete naturally, such landmines are guaranteed to become in-active within 90 days (at a 99.999 % reliability) . . . vice 30 or more years for traditional "dumb mines." And self-destructing/self-deactivating anti-personnel landmines pose virtually no threat to civilian life once a battle is over. But under the comprehensive international ban we seek, use of even these smart mines would also be ended.

Most countries cannot afford technically sophisticated self-destructing/self-deactivating anti-personnel landmines. And if we ask them to give up their dumb anti-personnel landmines, we have asked them to give up all they have, while we continue to use the more responsible self-destructing/self-deactivating model. In agreeing to give up our smart mines, the United States has taken the moral highground and has set the example for other countries regardless of their anti-personnel landmine inventory.

The anti-personnel landmine crisis has commanded this administration's attention from the very start. President Clinton has aggressively pursued a comprehensive worldwide ban on the production, stockpiling, transfer and use of all anti-personnel landmines. And we provide training, equipment and funds to help those nations most threatened by mines. Thanks to the vigilance and hard work of Senator Leahy and others like him, Congress passed a unilateral moratorium on the transfer of anti-personnel landmines in 1992. That moratorium has now been extended to the year 2000. In 1994, the United States spearheaded a successful resolution at the United Nations to ban exports of the most dangerous kinds of landmines. Also in 1994, the president dedicated the United States to eventually eliminating all anti-personnel landmines.

In May of this year, the president announced a series of actions the United States would take to pursue that goal. He ordered an immediate ban on the use of so-called dumb antipersonnel landmines – those which remain active until detonated or cleared. The only exception will be for those mines required to defend our troops and our allies from aggression on the Korean Peninsula and those needed for countermine and humanitarian demining training purposes. The remaining stockpile of nearly 4 million anti-personnel landmines will be removed from our arsenals and destroyed by 1999.

The president's anti-personnel landmine policy strikes an important balance between military and humanitarian imperatives by carefully ensuring that essential U.S. military requirements and commitments to our allies will be protected. Until an international ban takes effect, the United States reserves the right to use self-destructing/self-deactivating anti-personnel landmines because there may be battlefield situations in which they are necessary to protect American lives.

The Administration is determined to end our reliance on landmines completely and has directed the Defense Department to find alternatives that will not pose new dangers to civilians. In compliance with that tasking, we are examining a wide variety of concepts, technologies and systems. But so far, we have found no analytical basis for recommending any particular alternative and a number of questions remain regarding operational concepts, operational effectiveness and development risk and cost.

But any replacement is likely to involve a combination of three elements: surveillance – a sensor mechanism like JSTARS, UAV-mounted sensors or ground sensors; the overfire – mortars, artillery or aircraft, for example; and the man-in-the-loop – the command and control element which ties the sensor to the precision lethal fire. Let me assure you that although we don't yet know what the solution will look like, technologies clearly exist and we are confident that we can develop a battlefield alternative to anti-personnel landmines.

The military has demonstrated a strong show of support for the President's anti-personnel landmine ban. Secretary Perry has said he looks forward to the day when anti-personnel landmines will not be used in Korea. Gen Colin Powell has said that he abhors landmines. Gen Shalikashvili, chairman of the Joint Chiefs of Staff, said the president's policy set a "prudent and responsible course that will lead to the elimination of all anti-personnel landmines, while continuing to protect American lives." He added that as practical solutions are pursued, our priorities must be to maintain warfighting superiority while concurrently protecting the safety of U.S. service men and women. In April, more than a dozen retired U.S. generals signed an open letter to the president which called the anti-personnel landmine prohibition "not only humane, but also militarily responsible."

The President's anti-personnel landmine policy also directs DoD to expand our humanitarian demining program. Demining is one of the most fundamental humanitarian missions that the United States can be involved in. The goal of our demining effort is to help countries establish long-term indigenous infrastructures capable of educating the population to protect themselves from landmines, eliminating the hazards posed by landmines and returning mined land to its previous condition. The program assists the host country in development of all aspects of mine awareness and mine clearance procedures, with the caveat that no U.S. personnel will clear landmines or enter active minefields. Under the auspices of my office, DoD is pursuing a vital role in humanitarian demining while improving the readiness of U.S. forces through the unique training opportunities and regional access afforded by demining activities.

Special operations forces are the primary U.S. military resource for the training programs. Civil Affairs units play a key role in developing indigenous demining entities and helping them to develop sustainable long-term programs. Psychological operations personnel conduct mine awareness programs which educate populations in affected areas regarding the dangers of land mines, what they look like, and what to do if a landmine is located. Special Forces units train host country nationals to train others in their country to locate landmines, to mark fields and to destroy the mines strewn indiscriminately on key roads, in villages and in fields.

One of the most heavily mined nations in the world is a also developing success story. Cambodia's program was developed by the U.S. military's Pacific Command in Honolulu. In a quarter-century of warfare, the Cambodian civil war has become infamous for its unrestrained violence, with an estimated one million deaths resulting from the takeover by the Khmer Rouge in the 1970s. Now out of power, the Khmer Rouge continue to fight. Both sides in the conflict have resorted to wholesale mining of the countryside to deny territory to their adversaries and to control and terrorize local people. As a result, Cambodia is now riddled with 8 to 10 million landmines. In 1994, we began a humanitarian demining program in Cambodia. Special operations forces trainers have conducted mine awareness, mine clearance, and medical and professional training for the Royal Cambodian Armed Forces and the Cambodian Mine Action Center. Our effort has helped reduce the rate of mine-related injuries from 300 to 100 a month.

This year, our new program in Laos follows the example set in Cambodia. Over 20 years have passed since the end of the conflict in Laos, yet a significant amount of land is still infested with mines. In concert with the Lao National Steering Committee and the United Nations Development Program, SOCPAC personnel established a national program, whose operations and training assistance are now being expanded. In Vientiane, mine awareness and clearance elements are assisting the UN Development Program in developing community awareness programs for both anti-personnel landmine and unexploded ordnance awareness and clearance programs and training schools. This is being followed by the establishment of two regional operations offices with clearance training centers.

To support full implementation of the Dayton Accords, we are currently leading an international effort to begin clearing millions of landmines scattered throughout Bosnia and Herzegovina. We provided $3.5 million to establish the Bosnian Mine Action Center and have pledged up to $15 million to continue demining operations this year. The Bosnia Mine Action Center operates under a UN mandate, coordinating all mine awareness, data gathering and mine clearance activities through three regional offices – one in each ethnic region of the country. It will eventually become an entity of the Bosnian government. A U.S. Special Forces team recently completed training of 155 Bosnian deminers representing all three ethnic communities. This brings the total to 250 Bosnian personnel trained in demining activities.

In response to the President's policy, our demining operation has expanded significantly. The number of countries eligible for assistance has increased from 9 in FY 1996 to 14 in FY 1997, with 10 additional countries being considered. During the same period, the number of U.S. personnel deployed for humanitarian demining operations has increased by 77 percent; the number of indigenous forces trained has increased by 133 percent; and the dollar value of equipment transferred has increased by 32 percent. Further expansion and initiatives are ongoing.

The President's anti-personnel policy also directs the Defense Department to undertake a substantial program for the development of mine-detection and mine-clearing technology and to share this improved technology with the broader international community. In Fiscal Year 1995, DoD began a $10 million dollar research and development program to develop simple, hopefully inexpensive, equipment that can assist countries in detecting and clearing landmines. During that year, 30 new demining technologies and equipment were developed.

In FY 1996, 13 items were evaluated. Congress authorized $14.7 million for the program in Fiscal Year 1997, in an effort to expand research and development. The humanitarian demining R&D program uses expertise from government, industry, academia, foreign countries, the United Nations and NGOs to produce practical solutions for locating and clearing minefields, and for detecting, marking, recording, reporting and destroying individual landmines. The ultimate goal is to place demining equipment in the hands of indigenous deminers, non-government organizations and contractors specializing in demining.

In Bosnia, where it will take nearly 30 years to clear the region's 3 million landmines with current technology, we are field testing numerous equipment and techniques in support of the humanitarian demining mission. My office manages a program, run by the Countermine Division at the Army's Night Vision and Electronic Sensors Directorate, that is identifying and evaluating technologies for mine detection and clearance. It is a highly successful program, as evidenced by the technology we have made available in Bosnia, as well as in other countries. For example, the first two mine-sniffing dogs employed in Bosnia are from our program . . . as are the barrels of liquid explosive foam (LEXFOAM) and backpack dispensers that are being shipped to the area as we speak. We also developed the mini-mine detectors and mini-flails now in Bosnia. The mini-flails, by the way, have received high marks from a number of general officers. In fact, the Army is considering ordering some of their own.

My office is working to develop and deploy additional equipment to Bosnia for use in humanitarian demining. I know that Mr. Hap Hambric, DoD's Project Leader for Humanitarian Demining Technology Development at the Army's Night Vision Laboratory at Ft. Belvoir, VA, has already talked to you in more detail about this equipment. Let me just say that we're also working to optimize the use of commercial construction equipment to dig up mines more easily and we are exploring the use of radar to detect mines.

The Administration's anti-personnel landmine policy puts the U.S. squarely on a path to eliminating landmines within our own military while leading international efforts to ban anti-personnel landmines. Largely as a result of our leadership, more than 30 countries have either declared formal moratoria on anti-personnel landmine exports or have other export controls in place. However, the most effective means available to the international community to control worldwide use of anti-personnel landmines is through strengthening applicable international law. In the case of landmines, this law is embodied principally in Protocol II on Landmines in what is commonly known as the Convention on Conventional Weapons, or CCW.

The CCW was negotiated by the international community in the aftermath of the Vietnam War to limit the use of conventional weapons which can cause unnecessary suffering or indiscriminate effects. But because it was universally recognized as weak on the issue of landmines, nations convened in Vienna last fall to negotiate ways to strengthen it. At that session and at subsequent review conferences, considerable progress was made on several points that will, when entered into force, go a long way toward reducing the humanitarian crisis by ensuring responsible use of anti-personnel landmines until a ban takes effect.

Protocol II requires that dumb mines be used only in marked and monitored areas and that the state laying the minefield be held responsible for the field until it is removed. Also, there was substantial agreement on technical specifications for reliability of self-destruct and self-deactivation for anti-personnel landmines used outside marked and monitored fields.

On detectability, all states agreed that anti-personnel landmines should have a relatively high metallic content to assist in mine clearing operations. Unfortunately, some states may require up to nine years after entry into force to comply with these important provisions. Protocol II also places the responsibility for maintenance or clearance of minefields on the party that laid the mines and requires that this responsibility be carried out at the end of active hostilities. The revised Protocol does not include all the improvements proposed by the United States. Nevertheless, it is a remarkable achievement that will, if widely observed, save many civilian lives and return killing fields to planting fields. And, although the Protocol stops short of a ban on anti-personnel landmines, it is a critical step on the road to our ultimate objective – the elimination of anti-personnel landmines.

At the United Nations General Assembly earlier this month, the United States introduced a resolution calling for an eventual ban on the production, stockpile, transfer and use of anti-personnel landmines. It is the fourth, and strongest, UN resolution that the United States has spearheaded to eliminate all anti-personnel landmines. We've already begun to consult with our allies on the best way to negotiate this agreement.

The U.S. has taken several other steps to address the APL problem. My office initiated a novel approach to basic mine awareness and mine avoidance lessons. With the outstanding work of AC Comics, we produced a comic book featuring the Superman character that graphically teaches children about the dangers of anti-personnel landmines. The comic book shows the superhero rescuing two Bosnian boys who are about to walk into a field of landmines. Superman also uses his x-ray vision to protect the boys from a booby-trapped house. Half a million comic books were printed -- in both the Latin script used by Bosnian Muslims and Croats and the Cyrillic used by Serbs -- and are being distributed to children in the region by the NATO-led peacekeeping force and the Mine Action Center in Sarajevo. We hope to design different versions for other countries where children are killed or injured daily by mines and ammunition.

My office also established a multidisciplinary humanitarian demining center at James Madison University in Virginia to serve as the clearinghouse for humanitarian demining information management. The center will provide single point access to a full spectrum of information, training, research, analysis and services in support of our humanitarian demining program.

Last year, we created and released the first ever worldwide mine database. MineFacts is a compact disk containing over 275 megabytes of information on 675 types of mines throughout the world. It presents illustrations of each type of mine, accompanied by a text describing the mine, the various names by which it is known around the world, and its country of manufacture. MineFacts is the most complete database of its kind.

My office also created a landmine database specifically for use by soldiers in Operation JOINT ENDEAVOR. The three disk set, called BosniaFile, contains critical information on the 36 landmines most commonly found in Bosnia. Data includes pictures, general information on the size and weight of mines, the metal content, country of origin and emplacement methods.

And we developed a Demining Web Site on the Internet to provide information on all aspects of anti-personnel landmines and their removal. This already popular web site is assisting the demining community in two important ways: by providing easy access to detailed technical and background information, and by facilitating communication among the participants in the fight against landmines.

CONCLUSION

Let me close by noting that in the time that I've been speaking to you, anti-personnel landmines have claimed another life. It is a complex technical, political and military problem that nevertheless requires immediate solutions. Our children deserve to walk the earth in safety. The Clinton Administration is committed to real solutions as quickly as possible. The president has put the United States firmly behind a responsible program to rid the world of these hidden killers. And he recently repeated his call to the United Nations General Assembly to negotiate a comprehensive international ban on anti-personnel landmines. This is one of the President's top arms- control priorities. Finally, I want to thank all of you for your dedication and ask for your continued commitment to demining technology and battlefield alternatives to landmines. We must find a responsible answer to this dilemma. Remember, we are only limited by our motivation and imagination in applying them. Thank you.

Opening Remarks for Session X on Humanitarian Demining and Mine Policy

Prof. Fred Mokhtari,
Norwich University
Session Chair

I am honored to be here, and to be among such a distinguished group of experts. I am also pleased to represent Norwich University at this symposium. Norwich University is the oldest private military college in the United States, founded in 1819 in Vermont, and naturally interested in anti-mine warfare and demining. I hope that with your support and enthusiasm we can look forward to a follow-up conference at Norwich next year, to consider the POLITICAL aspects of the mine problem.

On behalf of Norwich University's President, Rear Admiral Richard W. Schneider, my colleagues and my students, I congratulate the Naval Postgraduate School and Dr. Al Bottoms for having organized this symposium. Norwich would welcome cooperation with the Naval Postgraduate School in anyway possible. Indeed, Norwich is putting the finishing touches on an articulation agreement with the Naval War College today, to award masters degrees to Naval War College's non-resident students! Norwich University is interested in cooperation with other institutions in any academic field in keeping with its guiding values.

As a political scientist, I must admit, I see the "mine problem" to represent two different types of issues. One, concerns the technological aspects, and the other, the political ones. I am reminded of Alexis De Tocqueville's warning in his classic book Democracy in America written a hundred years ago that in a democracy elected leaders are more likely to do what is popular, than what is right. The political challenge we face, therefore, is to make what is right, that which is popular. Without political will, technology even if available, will not be utilized, and the mine problem will not be resolved.

What I am proposing is a task perhaps more difficult than the technological challenges of mine warfare and demining. I am proposing that all of us, whether in education, research, industry or the armed forces, redouble our efforts to educate the public, to make what is right what is popular as well.

Submitted by LTGEN Robert C. Gard, USA (Ret)

An Open Letter to President Clinton

Dear Mr. President,

We understand that you have announced a United States goal of the eventual elimination of antipersonnel landmines. We take this to mean that you support a permanent and total international ban on the production, stockpiling, sale and use of this weapon.

We view such a ban as not only humane, but also militarily responsible.

The rationale for opposing antipersonnel landmines is that they are in a category similar to poison gas; they are hard to control and often have unintended harmful consequences (sometimes even for those who employ them). In addition, they are insidious in that their indiscriminate effects persist long after hostilities have ceased, continuing to cause casualties among innocent people, especially farmers and children.

We understand that: there are 100 million landmines deployed in the world. Their presence makes normal life impossible in scores of nations. It will take decades of slow, dangerous and painstaking work to remove these mines. The cost in dollars and human lives will be immense. Seventy people will be killed or maimed today, 500 this week, more than 2,000 this month, and more than 26,000 this year, because of landmines.

Given the wide range of weaponry available to military forces today, antipersonnel landmines are not essential. Thus, banning them would not undermine the military effectiveness or safety of our forces, nor those of other nations.

The proposed ban on antipersonnel landmines does not affect antitank mines, nor does it ban such normally command-detonated weapons as Claymore "mines," leaving unimpaired the use of those undeniably militarily useful weapons.

Nor is the ban on antipersonnel landmines a slippery slope that would open the way to efforts to ban additional categories of weapons, since these mines are unique in their indiscriminate, harmful residual potential.

We agree with and endorse these views, and conclude that you as Commander-in-Chief could responsibly take the lead in efforts to achieve a total and permanent international ban on the production, stockpiling, sale and use of antipersonnel landmines. We strongly urge that you do so.

General David Jones (USAF, ret.)
former Chairman, Joint Chiefs of Staff

General John R. Galvin (US Army, ret.)
former Supreme Allied Commander, Europe

General H. Norman Schwarzkopf (US Army, ret.)
Commander, Operation Desert Storm

General William G.T. Tuttle, Jr. (US Army, ret.)
former Commander, US Army Materiel Command

General Volney F. Warner (US Army, ret.)
former Commanding General, US Readiness Command

General Frederick F. Woerner, Jr. (US Army, ret.)
former Commander-in-Chief, US Southern Command

Lieutenant General James Abrahamson (USAF, ret.)
former Director, Strategic Defense Initiative Office

Lieutenant General Henry E. Emerson (US Army, ret.)
former Commander, XVIII Airborne Corps

Lieutenant General Robert G. Gard, Jr. (US Army, ret.)
former President, National Defense University
President, Monterey Institute of International Studies

Lieutenant General James F. Hollingsworth (US Army, ret.)
former I Corps (ROK/US Group)

Lieutenant General Harold G. Moore, Jr. (US Army, ret.)
former Commanding General, 7th Infantry Division

Lieutenant General Dave R. Palmer (US Army, ret.)
former Commandant, US Military Academy, West Point

Lieutenant General DeWitt C. Smith, Jr. (US Army, ret.)
former Commandant, US Army War College

Vice Admiral Jack Shanahan (USN, ret.)
former Commander, US Second Fleet

Brigadier General Douglas Kinnard (US Army, ret.)
former Chief of Military History, US Army

Seeking Real Solutions to the Landmine Problem

Mr. Robert Sherman,

Director of Advanced Projects
U.S. Arms Control and Disarmament Agency,
Former Deputy Chief U.S. Negotiator
at the Convention on Conventional Weapons (CCW)
Review Conference

The anti-personnel landmine (APL) problem isn't a matter of philosophy or ideology. It's real civilians maimed or killed by real mines every day, and denied use of their land because of the threat of uncleared live mines. In landmine negotiations, the only measure of our success is the real landmine casualties and land denial we ultimately prevent.

The vast majority of APL casualties are caused by mines produced, exported, and/or used by Russia and China. These countries are also the most determined holdouts against mine limitations. I say this not to criticize these governments but to define the problem we face. At the end of the day, the issue will not be the purity of positions taken by the many nations who are not the problem. The issue will be the future humanitarian practices accepted and observed by the few nations who have been the problem.

CCW ACHIEVEMENTS AND LIMITATIONS

The root of the APL problem is the fact that most mines, by design, function for decades after emplacement. Another very serious problem is that many mines are non-metallic, and therefore not easily detected by humanitarian de-miners. Yet neither long duration nor nondectability is usually necessary for the military function of the mine. The focus of CCW, then, became to reduce the danger to civilians from APL, while at the same time allowing their effective military use. Within this context, CCW achieved some remarkable successes, neither trivial nor easily accomplished. These include

SHORT MINE LIFE. Unmarked APL must self-destruct with 90% reliability within 30 days of emplacement, and they must self-deactivate (exhaustion of a battery without which the mine cannot operate) within 120 days of emplacement with 99.9% overall reliability. A country may claim a 9-year transition period before implementing about half of these restrictions; the other half are effective upon entry into force. Once this restriction is implemented, lethal duration of unmarked APL will be days, where now it is years; casualties will be reduced by several hundred times.

DETECTABILITY. All APL must have 8 or more grams of iron equivalent, to facilitate humanitarian demining. A country may claim a 9-year transition period before halting use of nondetectable mines, but transfer of such mines is prohibited immediately.

PROTECTING DEMINERS. Anti-detector mines, which are designed to explode when a magnetic mine detector passes over them, are banned completely and immediately.

We would have liked to do still better. The United States sought to have no transition periods, 95% self-destruct reliability, mandatory detectability for anti-tank as well as anti-personnel mines, and mandatory verification. While we were unable to persuade the holdout states to go that far, these governments moved far beyond their positions of only seven months before the end of the conference. At that point, any agreement accommodating the holdout positions would have included no requirements for self-destruction or self-deactivation, and an unlimited transition period for detectability.

The bottom line, of course, is not who "gave up" what. The purpose of the conference was to protect civilians from mines. By that standard CCW will, if observed, succeed on a large scale. If it had been put into force and observed thirty years ago, there would be no humanitarian landmine crisis today.

TOTAL APL BAN: THE NEXT STEP

On May 16, 1996, President Clinton announced that "The United States will seek a worldwide agreement as soon as possible to end the use of all antipersonnel landmines. The United States will lead a global effort to eliminate these terrible weapons... and stop the enormous loss of human life." He directed that US forces immediately and permanently halt all use of long-duration mines except in Korea. He also announced that "Because of the continued threat of aggression on the Korean Peninsula, I have decided that, in any negotiations on a ban, the United States will protect our right to use mines there."

Clearly, even if CCW were universally observed and prevented more than 99% of APL civilian casualties, 100% is better. The only way to eliminate all APL casualties is to eliminate all APL. But the task before us is formidable.

In the near term, the U.S. must find an affordable and effective substitute for APL for the Korean situation. The seriousness of the threat to Seoul, and the challenge of finding an effective substitute for APL in countering that threat, should not be understated.

More enduring difficulties lie in the holdout states' attachment to the military use of APL. The Chinese tell us they will give up nuclear weapons before they give up APL; the Russians tell us the only popular concern they hear about APL is from mothers anxious that their sons in the Army have the means to defend themselves. We must have both these countries on board if the final agreement is to be more than cosmetic.

Banning Anti-personnel Landmines

Stephen D. Goose,
Program Director, Human Rights Watch Arms Project

I would like to thank Al Bottoms and the symposium organizers for inviting me to participate, and also for including this particular panel on mine policy in the program. I understand that the first NPS symposium did not have a policy dimension. I believe it is crucial that the practitioners and planners of mine warfare and countermine warfare -- the best and brightest of which are assembled here today -- understand the political environment in which they are operating. I have concluded from listening to the speeches during the first day and one-half, and from many private conversations, that most of those attending this symposium do not have that understanding..

There seems to be a widespread lack of knowledge about U.S. policy with respect to antipersonnel (AP) mines and about the rapid progress that has been made toward a comprehensive international ban on AP mines. Though I had not planned on it, I feel compelled to begin today with a clarification of the new mine policy announced by the President and Secretary of State and Secretary of Defense on May 16th. It is now the officially stated U.S. policy that *all* AP mines must be banned, and must be banned as soon as possible. It is *not* U.S. policy that just "dumb" mines be banned. Yet, General Sheehan yesterday characterized it that way. The brochure for this symposium characterizes it that way. General Gill yesterday went considerably farther and complained that in some quarters dumb and smart mines were being treated the same way, saying he was engaged in a battle of semantics and that a distinction must be made between self-destruct and non-self-destruct mines. General Gill's remarks strike me as nothing short of an attack on official U.S. policy. As an NGO, I regularly attack official U.S. policy, and will do so at some length in a few minutes, but I was quite surprised to hear an active duty officer do so publicly.

Let me read to you from the President's remarks on May 16:

"The United States will seek a worldwide agreement as soon as possible to end the use of all anti-personnel landmines. The United States will lead a global effort to eliminate these terrible weapons and to stop the enormous loss of human life.... Until an international ban takes effect, the United States will reserve the right to use so-called 'smart mines' or self-destructing mines as necessary.... But under the comprehensive international ban we seek, use of even these smart anti-personnel mines would also be ended."

I urge conference participants to heed these words. The President repeated them in a speech before the United Nations in September, and they are part of the U.S.-sponsored landmines resolution now before the General Assembly. The U.S. government has recognized that smart mines are ultimately part of the problem and that a total ban is necessary to solve the mines crisis. You should be concentrating on ways to get rid of smart mines, on ways to fulfill your military missions without smart mines, rather than ignoring or trying to reverse the policy.

Let me backtrack for a moment to discuss why the U.S. and so many other nations are now calling for a ban. Simply put, we have a humanitarian disaster on our hands. This is a symposium on "the Mine Problem," but I have heard almost no discourse about the mine problem as I know it, or as millions of people in Cambodia, Afghanistan, Angola, Bosnia and many other nations know it.. I say this not to belittle the importance of countermine warfare, but to emphasize the importance of the global context of the landmines crisis. The State Department estimates 26,000 people are killed or maimed by landmines each year, about one every twenty minutes, one during the course of my talk. The victims are almost always civilians, often women and children. Landmines cause more casualties after conflict has ended than during the fighting. More than 100 million mines are planted in more than 60 nations; there are another 100 million in stockpiles; the U.N. estimates some 2 million additional mines are laid each year. The horrific human toll is compounded by the socio-economic impact, as mines prevent access to fields, roads, rails, bridges. Nations like Mozambique or Bosnia achieve peace but cannot begin the process of reconstruction and development until mines are cleared. Refugees and internally displaced persons cannot return home. For these reasons, antipersonnel mines have been called, first by Human Rights Watch and later by Secretary of State Christopher, "weapons of mass destruction in slow motion."

The International Campaign to Ban Landmines (ICBL) believes that any use of AP mines is a violation of international humanitarian law. The weapon is inherently indiscriminate, and its use clearly fails to meet the proportionality test of humanitarian law: the short-term military benefits are far outweighed by the long-term human and socio-economic costs.

What is being done about the crisis? NGOs created the International Campaign to Ban Landmines five years ago. It has grown into the most diverse and successful coalition ever. The ICBL consists of more than 700 NGOs in more than 40 nations. It includes organizations involved in demining, victim assistance, rehabilitation, human rights, arms control, humanitarian relief, medical, veterans, religious issues and more. a senior UNICEF official recently said that the ICBL is "the single most effective exercise of civil society since World War II." The ICBL has two calls: for a comprehensive ban on the use, production, stockpiling and export of antipersonnel mines, and for increased resources for humanitarian mine clearance and victim assistance programs.

Though many participants here may be unaware, the successes of the ban movement are stunning, especially over the course of the past year or year and one-half. The movement has quickly grown beyond just NGOs, and has been endorsed by the ICRC, UNICEF, UNHCR, UNDHA, U.N. Secretary-General Boutros-Ghali, and the most influential media sources, such as the New York Times and the Economist.

Under pressure, governments began coming on board. Belgium became the first nation formally to legislate a total ban in March 1995, Norway followed suit in June 1995. Also under pressure, nations agreed to review and revise the Landmines Protocol of the 1980 Convention on Conventional Weapons, a process that took two and one-half years. Negotiations were supposed to end in October 1995, but deadlocked with governments wanting to protect their own mine stocks and methods of using them. At that time, the ICBL could count only 14 governments that had publicly stated support for a complete ban. The negotiations finally concluded on May 3, 1996 and the results were sharply criticized by the ICBL as unlikely to make an significant difference in the humanitarian crisis.

Still, it was clear on May 3 that an ever-growing number of governments recognized the insufficiency of an approach based on complicated restrictions and technical fixes, and that a comprehensive ban was the only answer. Many governments are now out in front of the U.S. on this issue.

* We now have more than 50 pro-ban governments. The U.N. General Assembly resolution calling on nations to "pursue vigorously" an international ban and to conclude a ban agreement "as soon as possible" was passed by the First Committee on October 31 by a vote of 141-0, with 10 abstentions. Clearly, a new international norm is emerging.

* More than 50 governments have prohibited export of AP mines. U.S. intelligence indicates that there have been no significant AP mine exports globally in over two years.

* Some 30 nations have already unilaterally suspended or banned use of AP mines, including Germany, France, Canada, Australia, Belgium, Norway, Portugal, Austria, Denmark, the Netherlands, Switzerland, South Africa and the Philippines.

* More than 20 nations have prohibited the production of AP mines, and begun destroying stockpiles, including Germany, France and Italy.

* The Organization of African Unity has endorsed a total ban. The Organization of American States adopted a resolution in June 1996 calling for the establishment of a hemispheric mine free zone. The six Central American states declared themselves the first mine free zone in September 1996.

Perhaps the key event was the Canadian government sponsored conference held in Ottawa October 3-5, 1996. This brought together 50 pro-ban governments which agreed to a Final Declaration calling for a comprehensive ban and, more importantly, a Chairman's Agenda for Action, which laid out concrete steps for achieving a ban rapidly. And in a dramatic announcement at the end of the conference, Canada's Foreign Minister Lloyd Axworthy stated that Canada would host a ban treaty signing conference in December 1997. The international community now has a deadline for agreeing to an international ban, and a roadmap for getting there. The conference also featured perhaps unprecedented cooperation between governments and NGOs, which has continued in the wake of the Ottawa conference. There has been great enthusiasm for what might be called the Ottawa process, with various nations offering to host preparatory meetings leading up to a treaty signing in December 1997. It is too early to tell how many governments will come to Ottawa to sign a ban treaty; I believe it will be more than 50, with significant numbers from the developing world, where mines have been used most extensively. It is doubtful if Russia or China will attend, but I believe they will be most effectively brought in as international pressure builds and they can be stigmatized for operating outside the international norm. The real "problem" states are not Russia and China, but the user states and the affected countries, and it appears many of them will participate in the Ottawa process.

The U.S. has been decidedly cool to the Ottawa process. The U.S.-sponsored UNGA resolution calls for conclusion of a ban treaty "as soon as possible," but December 1997 appears to be too soon. Instead, the U.S. is considering half-measures and a step-by-step approach that will slow down momentum toward a ban and possibly undermine the Ottawa process. The U.S. has refused to take steps at home that would turn its words into actions: changing its temporary export moratorium into a permanent ban; adopting a production moratorium or ban; removing the exceptions for use of dumb mines in Korea and smart mines anywhere.

I believe the U.S. is taking a go slow approach because of concerns expressed by the Joint Chiefs of Staff and the regional Commander-in-Chiefs that alternatives to AP mines have not yet been developed. Yet, fourteen of our most distinguished retired generals told President Clinton in a full-page open letter in the New York Times, "Given the wide range of weaponry available to military forces today, antipersonnel landmines are not essential. Thus, banning them would not undermine the military effectiveness or safety of our forces, nor those of other nations." They also said, "We view such a ban as not only humane, but also militarily responsible." Those who signed include General Jones, former Chairman of the JCS, General Schwarzkopf, Commander Operation Desert Storm, General Galvin, former Supreme Allied Commander Europe, and General Hollingsworth, former I Corps in Korea.

We should not forget the dangers posed by mines to U.S. soldiers and peacekeepers. General Sheehan yesterday told us that mines are a force equalizer that negate the U.S. technological advantages and can inflict unacceptable casualties. He said they are the "war we are not prepared to fight." In Bosnia, landmines have claimed 224 UNPROFOR victims and 64 IFOR victims.

I conclude by saying that there is going to be a ban on all antipersonnel landmines. It is only a matter of when, and the December 1997 target date has been established. We should not respond to a crisis, in which 70 civilians die each day, with a go slow approach. We cannot wait for alternatives, for the six to ten year research, development, testing and procurement cycle. This requires bold action, unilateral steps, and true international leadership from the U.S. Finally, it also requires that you -- the mine warfare planners and practitioners -- get on board. Thank you.

Technology and Humanitaring Demining

Garth Barrett

Mechem International

We, in the commercial de-mining companies, see de-mining, when the conflict is over and some sort of peace agreement is in place, as a three phase concept, as follows :

PHASE I : Urgent immediate de-mining by the military forces deployed to assist the peace process. This will mean route, observation points and base clearance. This process only eliminates about 5-10% of a country's land mine problem.

PHASE II : Continuing military de-mining to expand the military forces abilities. Commercial companies conduct de-mining on mainly route clearance for humanitarian aide to be distributed, as well as associated area clearance. This process, as in Phase I, only eliminates another 5-10% of the mines in the ground.

PHASE III : General de-mining takes place with local personnel (military and civilian) assisted by commercial companies.
Foreign military personnel, such as US Special Forces may train local government forces in de-mining.
This process must deal with the bulk of the mine problem, with up to 90% still to be eliminated.

The conflicts, which have created this land mine pollution, are normally found in poor countries, which, if not impoverished prior to the conflict, have become so through the fighting. Therefor, their ability to pay for and absorb technology can be very limited. The military forces monitoring the peace do not transfer technology in Phase I or II and commercial de-miners will not normally do so in Phase III, unless specifically contracted to perform this service. However, the US, through the Special Forces and other countries, do assist with training and the transfer of acceptable technology in this phase, Phase III.

Commercial de-mining companies are frequently beset by a lack of understanding of the mine problem and are sometimes expected by international agencies, coached by other world organizations, who place contracts, to have "expert" personnel available in some sort of "warehouse" and, who must be "held over" and guaranteed until the contract is placed. This is very often commercially impossible and unreasonable, as mine clearance contract placements can sometimes take many months. Commercial de-miners must not only be totally professional de-miners, but also be well versed in the problems of Unexploded Ordnance (UXO), as this poses serious problems in most post conflict scenarios.

Some AID organizations require that only local civilian and ex military personnel from the mine polluted country should be employed in de-mining, in order that they benefit financially from the de-mining. This is very laudable, in that it assists in the financial well being of the local community, but it is unfortunately extremely inefficient in getting the job done. It has been stated that approximately 80,000 mines are being cleared each year in de-mining operations and up to 1,000,000 mines are being laid, therefor we are seriously losing ground under the present system. With the estimated 80-100Million mines that are already in the ground, there is a major need to address this issue.

The need for the military to maintain speed and momentum in military mine clearance has been stated many times, but this needs to be also a principle in humanitarian de-mining. As an example in Somalia, the commercial de-miners speed across the ground was at best 1km per day, whereas in Mozambique we averaged just under 20kms per day, which has also been maintained in Angola. This speed over the ground was made possible by using advanced technology in the form of mine and ballistic protected vehicles and our explosive vapor detection system. This vapor detection system eliminates the need to check areas with no mines, which besets most de-miners. As another example, using four personnel and three vehicles it was possible to clear 22,000 anti personnel mines in Mozambique in three months of work.

The vision of de-miners conducting de-mining with almost the same equipment used in World War II, has to change, if the task of clearing the world land mine problem is to be accomplished, within the next two decades. Otherwise, we will still be de-mining into the 22nd century. Laboratories that produce equipment for the de-miner need to have de-mining experienced personnel assisting them with the practical issues of humanitarian de-mining, which not only deals with land mines, but UXO, as well as improvised explosive devices. The mined areas of the world are "dirty", with all forms of explosive complications which can pose all sorts of problems for high tech equipment. These areas are, in most cases, battlefields. We need to get equipment out of the "sand box" and into the hands of operational de-miners hands.

We, in the US, need to find a means of combining commercial company personnel with our Special Forces operating in foreign countries. Our Special Forces, when they are training local government de-mining forces, are prohibited from entering a mine field, which limits their effectiveness. It has also been an unfortunate problem that, after our special forces personnel leave the country with the mine problem, many of the de-mining efforts slowly wither and die. However, with a commercial partner with stay behind, specialy tailored training materials in the program, their personnel could carry out this final essential part of the program.

During this conference, we have heard about the vast sums of money being spent in the political arena in connection with de-mining, but unfortunately very little of these funds are reaching the rural areas that have the mines in the ground, where the problems actually exist. We, as commercial de-miners, accept that, without the political awareness and motivation, very little will be achieved. However, it is also frustrating to see the manipulation of the mine problem by many governments, whose countries are infested with land mines. The powers that be need to find a formula, that can be translated into meaningful action on the ground, where the real problems exist.

Whilst the ban on anti personnel mines and the destruction of these mines in certain stock piles are greatly welcomed, we need to remember that there are still 80-100 Million mines in the ground, which need our urgent attention, if we are to reduce the world financial drain and economically uplift the populations suffering from this form of pollution !

Bringing New Technology to Bear on Landmine Detection: The Role of NGOs as Catalysts and Liaisons Between Technology Providers and the Mine-Affected Countries

Richard M. Walden
President, Operation USA

Operation USA and its new subsidiary "Operation Landmine: A Project To Rid The World of Anti-Personnel Landmines" have been working on various aspects of the landmine problem since 1979--initially through the provision of prosthetics programs in Cambodia, El Salvador and Nicaragua and more recently (1994-the present) as representative of 160 U.S. NGOs at a series of landmine conferences in Geneva, Copenhagen, Ottawa, Washington, Cambridge (MA.) and Tokyo.

Nongovernmental Organizations (NGOs) have stood by and watched as crawl & prod methods, relatively few dog teams and largely ineffective metal detectors and crude radars have been the order of the day in mine detection. Most NGO activity has focused on banning landmines and/or on providing prosthetics to mine victims or mine awareness training to potential victims. What was considered an exclusive area for the military and its private contractors--de-mining tehnology--is now attracting NGO interest in an attempt to stimulate the re-engineering of existing advanced technology and bringing it to bear in the minefields. NGOs have the field experience, the contacts and the staff to provide the critical linkage between emerging demining technologies and tools and the people they need to serve.

The above activity fills a huge void. There are at present hundreds of signatory NGOs to the International Campaign To Ban Landmines and dozens of NGOs active in prosthetics and mine awareness programs in mine-affected countries. Until now, there were virtually no NGOs working on marrying advanced technology to the detection, mapping and destruction problems. The crawl and prod method, teams of dogs and largely ineffective metal detectors are the most common methods in use. Statistical outcomes from the global $60-80 million annual humanitarian demining budgets are paltry in terms of land cleared and mines deactivated; mine laying still outstrips mine detection by 25 to 1.

NASA recognized this and--at our urging and in conformity with its technology transfer responsibility--set up the "Robotics Roundtable on Demining" at its Western Center on Technology Transfer in Los Angeles.[see attached background information]. The Roundtable has attracted the participation of the Lawrence Livermore National Lab, the Jet Propulsion Lab, Lockheed-Martin, Hughes, Lear Astronics, USC and the Defense Department's Humanitarian Demining Unit.

That the science exists to find and destroy implanted AP mines is becoming clear. That its re-engineering in affordable, maintainable, and mass producible quantities will happen anytime soon is the challenge at hand.

NGOs have an emerging role in this area, which had heretofore been considered a military domain. The major NGOs have long-term relationships both with mine-affected countries and with corporate donors to their programs. Major technology companies have yet to set up or sell any of their products to the poorest of the mine-affected countries. They also do not directly provide de-mining services of any kind. In order for them to become involved, NGOs have to make the case that de-mining makes good business sense and is, in fact, a multi-billion dollar opportunity to the company or companies that can convert defense, space or other related technologies and bring them to bear on the landmine problem. Their path to the mine-affected countries will be through NGOs already field operational.

Operation USA has been asked to co-chair the conference on landmine technology (Dec. 2-3) hosted by the publisher of White House Weekly and Defense Week magazines. This conference seeks to build on the outcomes from Monterey and from its predecessor conferences. The conference's goal is the same: to stimulate the private and governmental technology sectors to convert existing technologies in the defense, space and intelligence-gathering fields to mine detection. The Livermore Lab is doing just that with $600,000 of its own funds and we expect other labs and companies to follow suit.

PROGRAMS IN DEVELOPMENT

Land Mine Clearance: New Technology

The roads, paths and fields of 64 countries are littered with 110 million land mines, which kill or injure more than 20,000 civilians a year. Two to five million new mines are planted every year — twenty to fifty times more than are cleared. Policy makers are discussing banning land mines, but the prospect of this occurring soon is minimal.

Operation USA is promoting the development of efficient high tech alternatives to decades-old technology and substantial human labor presently used for demining. Operation USA is working with NASA, whose "off the shelf" space technology involving robotics, satellites and sophisticated sensors, is well suited to mine clearance.

Our goal is to hasten the re-engineering and deployment of robotics-based demining technology, and to arrange its first field test in 1996 in the mine fields of Cambodia, which currently claim the lives and limbs of 4,000 people yearly

HealthCorps Vietnam

Operation USA's 16-year commitment to the people of Vietnam has led to our most ambitious health development program. HealthCorps Vietnam will combine the knowledge, experience and dedication of doctors and public health personnel in both the United States and Vietnam to improve the health status of impoverished Vietnamese. It will balance public health programs, medical training, technology transfer and health care systems development to foster greater accessibility and self-sufficiency in Vietnam's provision of health care

By training local health professionals and introducing suitable medical technology, HealthCorps Vietnam will help Vietnam match its rapid economic development with advances in caring for the basic health needs of its people.

Organizations Calling for a Ban

Partial listing of over 450 NGOs in over 30 countries

Afghanistan
Afghan Coordinating Agency for Afghan Relief
Afghan NGO Coordination Bureau
Afghan Technical Consultants
DAFA
MDC
Mine Clearance Planning Agency
Organization for Mine Clearance & Afghan Rehabilitation
Radda Barnen, Peshawar
SWABAC

Austria
Greenpeace Austria
NGO Committee on Peace
Pax Christi Austria
World Peace and Relief Team

Australia
Human Rights Council of Australia
Medical Association for the Prevention of War
Mercy Refugee Service of Australia
People for Nuclear Disarmament QLD

Belgium
European Network Against the Arms Trade
Handicap International
Médecins sans Frontières International*
Oxfam Belgium
Pax Christi Flanders

Cambodia
Church World Service
Coalition for Peace and Reconciliation
Khmer Women's Voice
NGO Forum on Cambodia

Canada
Canadian Council for Refugees
Lawyers for Social Responsibility
Physicians for Global Survival

Denmark
DanChurchAid
Handicap International

France
ACAT (Action Catholique pour l'Abolition de la Torture)
Action Nord Sud
Agir Ici
Comité Catholique contre de Faim et Pour le Développement
Fondation France Libertés
French Committee of UNICEF
International Association of Peace Messenger Cities
World Union of Martyred Cities

Germany
Brot für die Welt
BUKO
Caritas Germany
IPPNW Germany
Komitee für Grundrechte und Demokratie
Netzwerk Friedenskooperative

India
Indian Institute for Peace, Disarmament and Environmental Protection
Solidarity for Peace

Ireland
Pax Christi Ireland
Oxfam UK/Ireland
Trocaire

Thailand
Asian Human Rights Commission
Handicap International BKK
IFSD
International Network of England Buddhists
Jesuit Refugee Service
Justice and Peace Thailand
Nonviolence International

United States
American College of Physicians
American Fracture Association
American Friends Service Committee
American Public Health Association
American Refugee Committee
Americans for Democratic Action
British-American Security Information Council
CARE
Center for Defense Information
Church of the Brethren
Church World Service
Commission on Peace & Justice, Episcopal Diocese of Massachusetts
Council for a Livable World
Demilitarization for Democracy
Episcopal Church – General Convention
Evangelical Lutheran Church in America, Division for Church in Society
Federation of American Scientists
Friends Committee on National Legislation
Interaction
International Human Rights Law Group
International Rescue Committee
Jesuit Refugee Service/USA
Landmines Survivors' Network
Maryknoll Fathers & Brothers, Justice & Peace Office
Mennonite Central Committee
National Council of the Churches of Christ in the USA
Oxfam America
Peace Action Education Fund
Save the Children U.S.A.
20/20 Vision National Project
Unitarian Universalist Association of Congregations
United Church Board for World Ministries
U.S. Catholic Conference
U.S. Committee for Refugees
Veterans for Peace
Women's Commission for Refugee Women and Children
World Vision International

Italy
AIFO – Associazione Italiana Amici di Raoul Follereau
CIES – Centre for Development Information and Education
EMERGENCY*
FOCSIV – Federazione Organismi Cristiani di Servizio Internazionale Volontario
IRES Toscana
Mani Tese
Pax Christi Italy
Servizio Civile Internazionale

Israel
Association of Israeli-Palestinian Physicians for Human Rights

Kenya
Maendeleo Ya Wanawake Organization
People for Peace in Africa

Malaysia
Asia-Pacific People's Environment Network
Just World Trust

Mozambique
Mozambican Association of the Handicapped (ADEMO)

Nepal
Women Development Society

The Netherlands
AMOK
International Fellowship of Reconciliation
Johannes Wier Foundation for Health and Human Rights
Pax Christi

New Zealand
CALM – NZ Campaign Against Landmines

Norway
Norwegian People's Aid

Philippines
Coalition for Peace
Gaston Z. Ortigas Peace Institute
Jesuit Conference of East Asia
National Council of Churches in the Philippines
Peace Studies Institute
Philippine Peace and Solidarity Council

South Africa
Ceasefire Campaign
Centre for South-South Relations
Group for Environmental Monitoring

Spain
Greenpeace Spain
Catholic Overseas Development

Sweden
Greenpeace International*
Radda Barnen
Swedish Peace & Arbitration Society

Switzerland
International Catholic Child Bureau
International Federation Terre des Hommes
Lutheran World Federation*
UNICEF Geneva

Taiwan
Association of Southeast and East Asian Catholic Universities

United Kingdom
British Refugee Council
Campaign Against Arms Trade
Ex-Services Campaign for Nuclear Disarmament
Jaipur Limb Campaign
Just Defence
Med Act
UK Working Group on Landmines

What You Can Do

- Endorse the Call for a Ban.
- Get your organization to join the Campaign.
- Educate the public and media.
- Urge your government to stop production, stockpiling, trade, and use of landmines.
- Urge your government to support the United Nations voluntary trust fund and other programs for mine clearance and mine victim assistance.
- Stigmatize the producers, exporters, and users of landmines.
- Contact organizations on the back of this brochure for more information and for a complete list of participating organizations.

Facts About Landmines

Average number of people killed or injured worldwide each year	26,000
Average cost of a landmine	$3 – $30
Cost to clear a landmine	$300 – $1000
Average number of landmines produced each year	10 million
Number of countries with landmine incidents	60+

Nations most affected by landmines
Afghanistan, Angola, Cambodia, Eritrea, Ethiopia, Iraq, Kuwait, Mozambique, Somalia, Sudan, former Yugoslavia

Major producers and exporters of landmines over past 25 years
Belgium, Bulgaria, China, former Czechoslovakia, France, Hungary, Italy, former Soviet Union, United Kingdom, United States, former Yugoslavia

RESEARCH AND DEVELOPMENT IN SUPPORT OF HUMANITARIAN DEMINING - Meeting the Landmine Challenge

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ABSTRACT

As part of an international humanitarian demining effort, Congress provided the Army $10M of FY95 RDT&E funds with direction to develop and demonstrate technologies applicable to humanitarian demining and other Military Operations Other Than War (OOTW) situations. Congress further directed that the technologies developed under this one-year only program be shared in an international environment.

The diversity of the mine threat pointed to the need for different types of equipment to detect and clear mines. The short time frame of this program dictated a development effort that maximized the use of existing technology. The requirement to develop equipment for use by host nation deminers with very different languages, cultures and education levels added to the challenge.

The FY1995 Humanitarian Demining Technology Program focused on technologies for the detection of metallic and non-metallic anti-tank and anti-personnel mines, low-cost mine clearance / neutralization systems, low-cost protective systems for personnel and clearance vehicles, highly-reliable clearance verification techniques and procedures, and on training initiatives to assist other countries in developing effective mine awareness programs. The goal of this program was to provide, on a quick reaction basis, the means to detect all land mines, both anti-tank and antipersonnel, while achieving near perfect clearance / neutralization and operator safety; to provide special purpose hand and small power tools optimized for demining operations; and to expand the contributions of the United States to train and assist other countries in developing effective demining programs. Identification and prioritization of demining needs and sustainment issues took place in coordination with representatives from the theater Commanders-in-Chief, the National Security Council's Interagency Working Group (IWG) on Mine Control and Humanitarian Demining, and Special Operations Forces. A Research and Development sub-group to the IWG provided scope and focus to the developmental activities.

The US Army CECOM Night Vision and Electronics Sensors Directorate (NVESD) developed and demonstrated some thirty items of equipment for mine detection, clearance, and training media for demining training with potential applicability to support of US forces deployed to Bosnia. This equipment included detectors, vehicle based clearers, in-situ neutralization devices and small, simple hand and power tools optimized for the demining role.

I. INTRODUCTION

This paper provides an overview of the Humanitarian Demining Technologies Development Program. The Countermine Division, Night Vision and Electronic Sensors Directorate (NVESD) of the US Army's Communications and Electronics Command is the Army executive agent for this DoD effort to develop internationally transferable technology for post conflict remediation of landmines and unexploded ordnance. This paper includes an overview of the global landmine problem, the US military's role in the global demining effort, research and development of technologies for humanitarian demining performed to date, and the types of technologies sought by the DoD FY1997 - FY2003 program. Although this document concentrates on technology applications for humanitarian demining, there is a great deal of common ground for application to Battlefield Unexploded Ordnance (B-UXO), UXO remediation (UXO-R), Explosive Ordnance Disposal (EOD) and Land Countermine needs.

A. Genesis of the Landmine Problem

Since the mid 19th century, landmines have been an important and prolific weapon of warfare. Their low cost and ease of employment provides military forces with an ideal economy of force measure in any battle scenario. A relatively small force can severely limit the ability of an opponent possessing greater firepower and mobility to maneuver, while minimizing or eliminating exposure to itself. Although long an accepted part of warfare between military forces, world events have evolved to an era where innocent civilians are now the primary victims of landmines.

In spite of an international effort to ban landmines for humanitarian reasons, they remain very much a part of the

world's arsenal of military weapons. The end of the cold war has not eliminated the potential for full scale warfare between military forces that would include the use of mines. They figure prominently in the war fighting doctrine of potential US adversaries such as North Korea and Iraq. This fact prevents the United States from completely rejecting the use of landmines by her military forces. It also illustrates the unfortunate fact that landmines may remain a serious worldwide problem for the foreseeable future.

The proliferation of landmines in the underdeveloped world is the most significant cause of the high number of civilian casualties. They are a prominent weapon in these regions because they are so effective, yet so inexpensive and easy to make. Landmines are frightening residual weapons of war that retard resettlement and economic renewal. This menace denies access to roadways and other lines of communication, villages and urban areas, agricultural fields and other rural areas long after the declaration of peace. Their numbers and the devastation they extract are staggering. When released in early 1995, the Department of State publication *Hidden Killers, the Global Landmine Crisis* estimated that some 85-110 million mines in 62 countries maim and kill approximately 26,000 people a year. The problem is most acute in underdeveloped nations already ravaged by conflict and that lack the resources and the infrastructure needed to deal with their landmine problems. The removal and destruction of all forms of dangerous battlefield debris, particularly land mines and other UXO, are vital pre-requisites for a country to recover from the aftermath of a war.

B. The Landmine Problem is Tough to Solve

The development of new demining technologies is a difficult task because of the tremendous diversity of environmental conditions in which mines are employed and because of the wide variety of landmines. Mines range in size and type from anti-personnel models small enough to fit into the palm of a child's hand to large anti-tank mines. There are different activation mechanisms such as pressure, electronic and command detonation. Mines use the blast effect from the explosion or flying fragments to injure or kill their victims. Manufacturers make mines from metallic and non-metallic materials. Fusing, lethality, and emplacement methodologies have evolved significantly since WW II. Full width attack, stand-off "side attack" and "top attack" mines are either in development or already in the inventories of several armies. This tremendous diversity makes the demining mission very complex and dangerous. Improvements in demining technology are critical to the success of any effort to reduce this threat to soldiers conducting peacetime contingency operations as well as to the civilian population.

Reports from US forces deployed in support of peace enforcement, peace keeping and post conflict humanitarian missions show that mines are the primary cause of personnel and vehicle casualties. The political impact of landmine casualties among US military forces can jeopardize the successful completion of peace operations. Casualties suffered by United Nations forces in Somalia demonstrated not only the effectiveness of mines as a weapon, but also how they can create politically unacceptable losses. The few injuries and deaths of Interim Forces (IFOR) personnel in Bosnia have already sensitized populations and national leaders to the effects of landmines.

The United States and other countries are working to eliminate the landmine problem. The plight of the many lesser developed nations suffering from severe landmine problems and the threat to US forces engaged in peace operations has led to an emphasis by the White House, Congress and the Department of Defense on the development of new technologies and equipment for mine detection and clearance. The development of these new technologies will improve the efficiency, safety and effectiveness of the demining process. Research and development programs to meet the countermine needs of tactical military forces and of peacetime humanitarian demining operations are now underway at the Night Vision and Electronic Sensors Directorate. Before describing the NVESD demining technology development program in detail, an understanding of the process used by the United States military to assist other nations with demining is of value. Knowledge of this process will provide a better understanding of the types of technologies that the demining community needs.

C. US Participation in Humanitarian Demining

Military forces, non-governmental organizations and contracted commercial enterprises have all been involved in demining. US military forces participate in the demining effort within limits established by US government policy. American forces may only perform demining for self-protection. American military forces involved in humanitarian demining will not enter an active minefield. Rather than perform actual demining, the US theater commands establish and support demining and mine awareness programs, and conduct demining training for indigenous personnel. Another important policy requirement is that deminers must destroy all mines where they find them. This is to prevent anyone from removing, stockpiling and re-using them in the future. These policy requirements have an important bearing on how DoD supports the demining effort, and therefore on the technology that it requires.

Planning, conducting and sustaining humanitarian demining operations requires coordinated participation from US military and other national intelligence gathering and mine warfare analysis assets. Several military organizations with expertise in mine warfare exist at commands responsible for training and doctrine and for material development. The expertise of the

Special Operations Forces (SOF) makes them the leading authority in this arena.

In any given regional area, it is important that all participants be integrated into a command and control structure to support the theater command's demining mission. The Special Operations Commands in each theater provide this demining command and control function for the CINC.

Prior to US involvement in a demining program, intelligence gathering from national systems and on-site human intelligence provide initial reports of mine warfare activities in the affected nation. During this phase intelligence assets look for positive indications of the presence of mines such as stockpiles, mine laying equipment, actual mine operations and casualty reports. More important, they search for areas not infested by mines to identify safe areas.

The above process determines the scope of the landmine problem in the affected nation. With this as a beginning, intelligence and other fact finding assets survey and analyze how and where the warring factions employed the mines. Electronic and in-place human intelligence assets will piece together the scope of mine use and the type of devices known or projected to be in the warring parties' inventory. Simultaneously, assessment teams led by the responsible theater special operations command will validate the threat. These teams may include representatives from the Joint Staff, the Department of State and various intelligence elements. This knowledge is important to theater command planners as they tailor the personnel, training and equipment requirements to the specific landmine threat in that nation.

The product from the above analysis is a list of known and suspected mines and booby traps, and their projected locations. Analysts then enter this data into a comprehensive mine/countermine database. The National Ground Intelligence Center maintains this database. It provides technical and tactical information on all known mines in the area. This is important information because the process to find and destroy a mine depends on its physical properties. The team simultaneously develops a database of known or suspected locations of mined areas. This tool is critical to planning and prioritization of humanitarian demining operations.

When a theater command completes its demining plan for a given country, the Commander-in-Chief forwards the plan to the Joint Chiefs of Staff for approval. Once approved by the Joint Staff and by the IWG, the theater command performs the mission. The Special Operations Forces (SOF) components assigned to the command execute the humanitarian demining program for the theater Commander-In-Chief (CINC). Policy and funding for the operations is provided by Deputy Assistant Secretary of Defense for Special Operations and Low Intensify Conflict (DASD(SO/LIC)).

US forces continue to receive updates of mine employment prior to and during deployment. In the near future, detection platforms carrying multi-spectral, integrated sensor systems capable of detecting mined areas and areas containing no mines will provide these updates. Initially, the identification of mine free areas is more important than plotting known mine fields. Identification of where mines are not will allow the population to begin food production and other important tasks to rebuild the economy in these areas while they mobilize the demining effort.

Mine awareness training is one of the most important parts of a humanitarian demining program, especially for returning refugees. Execution of this part of the demining plan is a combined effort between special operations, civil affairs units and the US embassy in that country. This mine awareness education requires effective training support equipment that would include a comprehensive mine database, and multi-medial assets to disseminate mine awareness programs of instruction, warnings and photos.

In addition to mine awareness training, the SOF component, with civil affairs and psychological operations participation, establish a training program for host nation deminers. The training and mine awareness program will vary from country to country based on the level of education and industrial capability. These characteristics of the nation involved are important factors to consider when introducing demining equipment. Establishment of a training program, and the types of equipment needed are also highly dependent on diversity of the mine threat in the host country, and the geographic and environmental make-up of the land. When considering the need for humanitarian demining around the globe, from desert to temporal to jungle climates, there is a huge challenge to optimize technology to make a meaningful difference in the elimination of landmines.

II. PROGRESS TO DATE

A. Program Description

Traditionally, countermine/mine requirements have addressed battlefield operations to support the pace of maneuver. Technology solutions for rapid surveillance, reconnaissance, detection, and neutralization portend significant countermine capability for maneuver forces needs to achieve requisite tempo, survivability, and battlespace management of countermine/mines operations. Humanitarian demining focuses on developing, testing, and evaluating the best available technologies that might be applied throughout the full range of demining requirements: locate minefields (or confirm their absence); detect individual mines; clear and destroy a large number of mines rapidly and safely; enhance the safety of deminers; and tools to facilitate mine awareness and deminer training. Humanitarian demining efforts leverage, where

applicable, the technology investments made for combat countermine as well as those investigated for remediation of defense sites, Explosive Ordnance Disposal (EOD), and the clearance of our training and test ranges.

Existing technology and equipment used for demining are slow, dangerous and man-intensive. During the past two years the US Department of Defense has engaged in a substantial effort to increase the efficiency and safety of demining with technology. As part of the international humanitarian demining effort, Congress provided the Army with $13M of RDT&E funds over FY95 and FY96 with direction to develop and demonstrate technologies applicable to humanitarian demining and other Military Operations Other Than War (OOTW) situations. Congress tasked the Army and its countermine scientists and engineers to solve unique humanitarian demining equipment requirements by leveraging new, proven and promising technologies that are capable of being used for demining and to share them in an international environment.

The diversity of the mine threat pointed to the need for different types of equipment to neutralize them. The short time frame of this program dictated a development effort that maximized the use of existing technology. The requirement to develop equipment for use by host nation deminers with very different language, cultures and education levels added to the challenge.

The FY1995-96 Humanitarian Demining Technology Program focused on training initiatives to assist other countries in developing effective mine awareness programs and on the development of improved demining technologies. Areas of interest for technology development were:

- Detection of metallic and non-metallic anti-tank and anti-personnel mines.
- Low-cost increased efficiency mine clearance and neutralization systems.
- Low-cost protective systems for personnel and clearance vehicles
- Highly reliable clearance verification techniques and procedures.

The goal of this program was to rapidly provide suitable technology to detect all land mines, achieve near perfect removal and neutralization and operator safety and provide special purpose hand and small power tools optimized for demining. This technology will allow the United States to expand her contributions to assist other countries in developing effective demining programs.

The demining staffs of the regional Commanders-in-Chief, the National Security Council's Interagency Working Group (IWG) and Special Operations Forces representatives identified and prioritized demining needs and sustainment issues. The Research and Development sub-group to the IWG provided scope and focus to the developmental activities.

In compliance with Congressional direction, the NVESD designed, developed and evaluated some thirty items of equipment for mine detection and clearance that are applicable to demining and peacekeeping type environments. Several of these prototype items performed so well that the United States deployed them to support American forces now engaged in peacekeeping and in demining operations. A by-item description follows this brief list of each humanitarian demining prototype technology developed to date:

- On/Off Route Mine Detection
  - Infra-Red (IR)/Ground Penetrating Radar (GPR) Mine Detector
  - Mini-mine Detector
  - Hand Held Trip-wire Detector
  - Ground Based Quality Assurance System
  - Vehicle Mounted Mine Detector
  - K-9 Program
- In-Situ Neutralization
  - Liquid Explosive Foam
  - Chemical Neutralization
  - Mine Marking and Neutralization System
  - Shaped Charges
  - Explosive Demining Device
- Mine Clearance
  - Improved Flail
  - Heavy Grapnel
  - Teleoperated Ordnance Disposal System
  - Mine Clearing Blades
  - Towed Light Roller
  - Berm Processing Assembly
- Individual Components
  - Extended Length Weedeater
  - Extended Length Probe
  - Command Communications Video and Light System (CCVLS)
  - Sonar Imaging
  - Vehicle Protective Kit
  - Demining Kit
  - Mobile Training System
  - Mine Locating Marker

- Blast and Fragment Container
- Blast Protected Vehicle

• Other

- Vehicle Towed Roller
- Mine Clearing Plow

B. On/Off-Route Detection

VEHICLE MOUNTED MINE DETECTOR (VMMD)

The Vehicle Mounted Mine Detector consists of a variety of sensors and real-time video transmission to detect on-road and off-route landmines. The VMMD uses IR and ultraviolet (UV) cameras for stand-off detection, and ground penetrating radar (GPR) for close-in detection. A FLIR Systems, Inc. Prism camera with a 30 degree diagonal Field of View (FOV) and a Noise Equivalent Differential Temperature (NEDT) of less than 0.1° C, and a Hammamatsu UV camera were the stand-off detectors used during the demonstration. This sensor combination increases the probability of detection and the efficiency of mine clearing.

The GPR close-in sensor detects and identifies buried landmines greater than or equal to 2 inches in diameter off-road and at least 8 inches in diameter on-road. The GPR subsystem couples two key technologies: sophisticated 3-D processing, and advanced frequency stepped radar. The intent of the frequency stepped approach is to permit operation at a radio frequency (RF) duty factor approaching unity, to remove the short pulse radar requirement that the RF equipment be instantaneously broadband, and to achieve a fully coherent radar capability while retaining the high range resolution capability. The frequency range is 700 to 4200 MHz, with 0.4 amplitude resolution, and a 90 dB dynamic range. The GPR's sensors are cantilevered in front of the vehicle on rails, with motors to scan the six foot wide 2 by 16 antenna array. Real-time visual detection and inspection are possible with the GPR system.

Besides the sensor suite, the VMMD consists of video cameras, a Global Positioning System to determine mine locations, remote controlled paint sprayers for marking, an operator's command station for operator controls, visual displays and control of sensor functions and parameters, and a skid steer loader vehicle.

A portable controller at the operator's command station allows access to the various remote sensor functions. The camera select capability permits the operator to select the video display source from the visual driving camera, the IR camera or the UV camera. The portable controller is small, lightweight and has its own self-contained power. A personal computer at the control center runs a geographical information system (GIS) display. The GIS is very easy to operate. It accurately displays the vehicle path, vehicle coordinates, the IR and UV targets received from the target recognition software, and the GPR detections.

MINI MINE DETECTOR

The Mini Mine Detector is a battery powered, hand held miniature metal detector. A deminer uses this device to detect buried anti-personnel and anti-tank mines with metal content ranging from several kilograms to as low as a gram. The Mini Mine Detector folds to be as small as possible when not in use. The unit can fit into a deminer's pocket, thereby being available at all times for emergency mine detection. The unit is also rugged and sensitive enough for everyday demining operations as a replacement for current systems that are much larger. An operator can easily use the unit while he is in the prone position. This reduces the deminer's profile in the event of an accidental mine activation. The system operates on 4 AA batteries which are commonly available worldwide, and also has a 4 D-Cell battery pack as backup for long mine detection operations.

HANDHELD TRIP WIRE DETECTOR

The handheld trip wire detector system gives a deminer on foot important visual aids to locate trip wires in front of him. This system consists of the following components:

a. A 3-5 micron handheld IR sensor with 256 X 256 (platinum silicide) Focal Plane Array (FPA) and 50mm lens.

b. A 0.5kW generator.

c. A 200 watt light bulb mounted in polished aluminum reflector. This component provides an outside (active) means to radiate the target area prior to using the handheld IR sensor.

d. A tri-pod and/or demining cart attachment brackets.

e. A 9" to 13" high resolution television monitor.

f. An 8mm or standard VHS recorder.

GROUND BASED QUALITY ASSURANCE

The Ground Platform Mounted QA Sensor Suite uses IR (3-5 micron and 8-12 micron), UV and video cameras to find surface and buried mines, trip wires and anti-handling devices.. The purpose of this system is to confirm that an area believed to be clear of mines is indeed mine-free. A covered, mast mounted platform houses the cameras. The camera assembly can mount to a vehicle or to a static ground position. Signals from the cameras transmit to a computerized control station. An operator at the control station can remotely operate the cameras. The system permits an operator to view an area on a computer screen from any one of the four cameras, and capture an image onto the computer's hard disk at any time. The operator can then import

the image into a program to enhance it in various ways to highlight a mine. By performing this technique on images from any combination of the cameras and comparing the results simultaneously on screen, a trained operator can distinguish a possible buried or surface mine. The software also includes Automatic Target Recognition (ATR) capability to designate probable mines for the operator.

VEHICLE MOUNTED DETECTION (VMD) SYSTEM

This on-road and off-route system detects buried or surface emplaced metal or plastic mines. Operators can rapidly switch the system between on-road and off-route configurations. The two configurations have a remote controlled vehicle with a mast mounted camera suite in common. The system includes a control station for the operator that permits control of the vehicle and sensor systems, and provides real-time output. The station also displays sensor data and video. The control station is both man-portable and able to fit in vehicle-mounted equipment racks.

Two interchangeable detection modules, each containing a metal detection array and a Thermal Neutron Analysis (TNA) sensor, give the system its on-road and off-route capability. The purpose of the TNA is to confirm that an object found by the metal detection array is a mine. The sensor uses a Californium 252 radiation source which emits neutrons that penetrate the ground. These neutrons cause the high nitrogen content of land mines to emit gamma rays that the sensor head analyzes. The TNA thus discriminates between metal objects with no explosive content and land mines. This greatly increases the efficiency of the demining process when compared to metal detection alone. With metal detection only, deminers must treat every object found as a mine until they uncover it and establish its identity. The system marks mine locations with a paint sprayer. To record and report mine location information, the system uses a combination of Global Positioning System (GPS) and wheel encoders.

K9 PROGRAM

Explosive materials in mines emit vapors that trained dogs can detect. This program demonstrated the effectiveness of dogs as mine detectors. The NVESD investigated two alternative K9 techniques:

- Free Leash. Under handler control, dogs operate in suspected mined areas and alert when they encounter a mine. The dogs alert by sitting down next to a mine when they detect it. Besides mine detection capability, the test also revealed that dogs are able to detect trip wires.

- "Checkmate" System. With this method, the dogs do not initially enter the mined area. Deminers place collector boxes at appropriate locations in suspected mined areas. The collector boxes are vacuum filters. They trap the scent of explosive material in the air if a mine is close to the box. Three methods exist for placing the collector boxes; by hand, from a vehicle mounted platform and from the air. When put in place, the collector boxes have markings showing their exact location. After a period of time, deminers retrieve the boxes and transport them to the dogs. When a dog alerts to a collector box, deminers can then perform a detailed search, using a free running dog, in the area from where they retrieved the box. Collector boxes that the dogs do not alert to indicate mine free areas. The Checkmate concept thus allows deminers to limit their effort to the areas indicated by the dogs.

C. In-Situ Neutralization

LEXFOAM

LEXFOAM is a nitro-methane based liquid explosive foam used for military and commercial blasting agents. It is effective at clearing or breaching mine fields, including those with sophisticated anti-tank and anti-personnel mines. The closed-cell structure of LEXFOAM gives this technology a greater shattering effect than devices using the same weight of high density explosive. A disposable initiation device permits safe initiation and detonation of both foam and mines. There are two configurations of delivery systems. A man-portable backpack configuration is for small or difficult to reach areas in a minefield. A palletized version is for large open areas of a minefield that are accessible by a commercial pickup truck or equivalent vehicle.

CHEMICAL NEUTRALIZATION

This effort involves the use of chemical approaches to neutralize mines in-situ. The chemicals change mine's main charge to an inactive state by burning or by detonation. Alternatives to be explored are:

a. Autocatalytic decomposition reaction with amines or metal alkyls in the absence of air (buried mines).

b. Heterogeneous chemical reaction with amines or metal alkyls in the presence of air (surface mines).

c. Detonation upon contact with interhalogens.

The program evaluated two versions of the delivery system, designated as Gun 1 and Gun 2, to get the chemical into the mine and in contact with the explosive. They both operate by firing a bullet into the mine to deliver the chemicals. Both systems are positioned above the target mine with a tripod. They differ as follows:

Gun 1: A small plastic bottle, approximately 1.5" in diameter and 3" high, contains the chemical. The capsule sits at the lower end of the tripod, just above the surface of the mine. A rifle caliber bullet, fired from above the capsule, goes through

the chemical filled bottle and continues into the mine. The chemical falls into the hole in the mine created by the bullet and neutralizes the explosive.

Gun 2: In this version, the neutralization chemical is inside the cartridge so there is no capsule. When fired, the bullet penetrates the mine casing, then releases the chemical to neutralize the explosive.

MINE MARKING AND NEUTRALIZATION

This product consists of a polyurethane foam that hardens after being dispensed. The foam impregnates the exposed parts of a mine and then hardens, which renders the fuze inoperative. The bright color of the hardened material clearly marks the location of the mine. A man-portable dispenser applies the foam. The hardened foam does not destroy mines, but it does make mines safer to handle for subsequent destruction. It also allows the capability to attach a rope to any kind of mine so that deminers can pull it out of the ground from a safe distance.

SHAPED CHARGES

Current mine neutralization shaped charges are too large to use on small anti-personnel mines. Another problem is that hazardous fragments from shaped charge detonations remain after the explosion. This program demonstrated the effectiveness of commercially available shaped charges. The oil industry uses varying sizes of shaped charges to create oil well bore holes. A selection of charge sizes allows the use of the optimum charge against a given size mine and reduces fragment waste. Shaped charges are also much less usable as ammunition compared to standard military charges.

EXPLOSIVE DEMINING DEVICE (EDD)

This device is a specially designed shaped charge mine neutralization munition integrated into a fixed time delay fuze assembly. It produces a penetrating jet stream, which neutralizes the mine. This design provides the mine neutralization capability of much larger charges. The EDD neutralizes anti-personnel (AP) and anti-tank (AT) mines, both buried and surface emplaced.

D. Mine Clearance

IMPROVED MINI-FLAIL

The Office of Science and Technology (OST) has already performed research with this small remote controlled clearer. The Mini-Flail is a small utility vehicle (based on a commercial Bobcat chassis) modified with a remote control kit, a rotating flail mechanism and armor protection. Its purpose is to clear anti-personnel mines from unimproved lines of communication and from off-road areas that are not accessible to large area mine clearers. Improvements to the original design are:

- Use of a new 3375 skid steer chassis from John Deer.
- Remote reversal of the rotation of the flailing head.
- Lighter armor in the flail cover and flail.
- Improved integration and protection of electronic controls and circuits.
- Improved tires to withstand blasts from AP mines and to spread weight on ground.

GRAPNELS

A grapnel is a tethered device used to clear trip wires and electrically fired mines. A spring loaded launching device propels the grapnel a to given distance depending on the length of the tether and on the launch force. As deminers reel the grapnel back towards the launch point, it activates trip wires to detonate mines a safe distance away.

The grapnel and launcher configuration will fit onto the demining cart (see below) to support demining operations in small or confined areas. A casting device throws the grapnel attached to a line from a modified deep sea fishing reel. An electric powered reel recovers the grapnel, which snags tripwires as it returns. The grapnel has some ability to extract itself from obstacles, but it is simple and inexpensive enough to be a throw-away item. A heavier grapnel, designed to be launched from a vehicle in less confined areas, is also under investigation.

TELE-OPERATED ORDNANCE DISPOSAL SYSTEM (TODS)

The TODS adds mechanical mine clearance capability to an off-the-shelf skid loader. TODS safely removes mines from sensitive or critical areas such as schools, hospitals and power stations. In addition, it also exposes (unearths) and places demolition charges onto mines that are too dangerous for people to approach such as deeply buried, highly sensitive or booby-trapped mines.

Modifications to the skid loader are a teleoperation (remote control) kit, detection capability and clearance attachments. Individual items on the vehicle include video cameras, a manipulating arm with a shovel and a gripping attachment, an air knife, a metal detector, a GPS subsystem, a vegetation cutter and blast deflectors. The modular command and control system allows remote control of each electronic, electromechanical or hydraulic device. The manipulator allows mechanical pick-up and placement of in-situ neutralization devices. The TODS will demonstrate the integration of a variety of sensors and clearing devices under remote control into an effective mine removal system.

The TODS depends on advanced knowledge of approximate mine locations. An on-board metal detector or video cameras pinpoint the exact location.

MINE CLEARING BLADES (MCB)

The program demonstrated the effectiveness of mechanical demining blades designed for attachment to commercial construction equipment. The purpose of these blades is to remove anti-tank mines from the path of the host vehicle, and collect or expose them for subsequent neutralization. To be most effective, MCBs could be used in conjunction with the Berm Processing Assembly and with anti-personnel mine detonating rollers. The NVESD tested two configurations of mine clearing blades.

The bucket design not only surfaces mines buried up to 10 inches deep, it does so without destroying a cultivated area's ability to grow crops. The shape and arrangement of the tines are similar to a field cultivator. The bucket scarifies the soil and leaves it in place just as a farmer would cultivate a field. At the same time, it brings buried mines to the surface for subsequent disposal. The bucket is still available for its designed use. It can therefore clear obstacles away from mines, fill craters left after a blast and protect the operator should the vehicle strike a mine. The mine clearing bucket is good for working in confined areas such as forested and urban settings.

The second configuration is a mine clearing rake that attaches to a bulldozer. The rake performs the same functions as described for the bucket, but for less confined areas like fields. The NVESD designed the rake especially for demining. Besides its ability to double as a cultivator, the rake does not have as many additional uses as does the bucket.

TOWED LIGHT (SWAMP) ROLLER

Light anti-personnel mine detonating rollers towable by small winches or animals will reduce the cost and increase the safety of demining in watery areas. Examples are wet vegetated areas and rice paddies. The availability of animals that can drive light rollers exceeds that of motorized vehicles in some countries.

BERM PROCESSING ASSEMBLY (BPA)

A proven method for clearing paths through a minefield is to use side casting blades similar to snow plows. A significant weakness of these devices for demining is that they leave a mine contaminated berm on one or both sides of the clearing vehicle. For mine clearing blades and plows to be acceptable humanitarian demining tools, a method to clear these berms must exist. A clearing vehicle tows the berm processing assembly. The BPA removes mines from an earthen berm by picking up the dirt and applying a mechanical filtering process to isolate AT from AP mines. The mechanism deposits AT and AP mines behind the BPA for subsequent neutralization. The BPA returns the processed soil back to the ground. With the AT and AP mines in plain view behind the path of the berm processor, deminers can neutralize them with much greater ease and safety than manually removing them from the berm.

E. Individual Components

EXTENDED LENGTH WEEDEATER

The NVESD evaluated two prototype extended length weedeaters to increase deminer safety in case of a detonation. One is a handheld model and the other is wheeled. Both are commercial off-the-shelf (COTS) weedeaters modified for use as a humanitarian demining tool. The modifications involved lengthening the shaft of the hand held version and extending the handle of the wheeled version. The purpose of these systems is to increase the safety of deminers operating in areas where vegetation conceals mines. It is also necessary to remove vegetation for ground coupling of detectors and visual or IR sensors.

EXTENDED LENGTH PROBE

The purpose of an extended length "smart" probe is to improve efficiency and safety for deminers as they manually probe for mines. Extended length translates to increased safety by positioning the deminer farther away from a potential blast. The addition of a blast shield near the base of the probe further enhances safety. A vibrator and sensor at the probe tip feeds audio signals to the operator. A trained operator determines if the buried object is manmade, and if so whether it is metal, plastic or wood. The operator thus has much more information prior to uncovering the object. There is potential for a sensor to feed signal information into a computer driven automatic target recognition (ATR) software algorithm. The computer could indicate to the operator whether the object being probed is a possible mine.

COMMAND COMMUNICATIONS VIDEO AND LIGHT SYSTEM (CCVLS)

The Command Communications Video and Lighting System (CCVLS) is a demining command and control system. It enables a technician to transmit real time audio and video from a demining work area back to a command post at distances up to one mile line-of-sight. This allows the operator at the command post to monitor and record all activity in the demining work area while greatly enhancing the safety and allowing the review of the actual demining procedures. The CCVLS is a self contained, rapid deployment field video and audio communications system. Three easily transportable cases house the system. Deminers use a low power, on-body 25 mW HERO safe transmitter to send and receive audio. A miniature helmet mounted video and light source combination transmits to a 25-foot safe radius from the mine. The CCVLS combines these signals, plus the video from a separate wide angle video camera

positioned outside the safe area, to the command post via RF link or coaxial link.

SIDE SCAN SONAR

The Side Scan Sonar detects and provides photographic quality images of very small targets, such as mines and ordnance in water with zero visibility. The operator can determine any variation to the normal environment and allow for pinpoint accuracy in marking target objects. The system uses a personal computer for control, display, and data storage functions. It also incorporates a fully integrated navigational plotter and software for image enhancement. The complete system consists of a towfish (600kHz), a coaxial cable, and an IBM compatible PC incorporating an interface board, cables and the software package.

MODULAR VEHICLE PROTECTION (MVP) KIT

Modular Vehicle Protection is an add-on kit for commercial vehicles to shield its occupants from a mine detonation. It consists of a molded Glass Reinforced Plastic (GRP) ballistic liner module and Aluminum Oxide Ceramic armor fastened to the vehicle interior floor, doors, firewall, rear wheel wells and rear cargo compartment divider. In addition, transparent armor attaches to the windshield, door windows and cargo compartment divider. Steel blast deflectors are in the front wheel wells.

DEMINING KIT

The demining kit consists of a hand cart or small rough terrain vehicle with a collection of hand and power tools for demining. Kit components will vary depending on the location and terrain involved. The initial kit component list follows:

a. The hand cart or small vehicle to carry equipment. The cart has a front-mounted protective shield for the operator.

b. Light grapnel mounted to the front of the cart.*

c. Weed eater.

d. Generator.

e. Air compressor.

f. Leaf blower.

g. Trowel.

h. Three pound hammer.

i. Wire cutter.

j. Pick-mattock.

k. Spade.

l. Mine probe and accessories.*

m. Explosion container.*

n. Chemical and/or explosive mine neutralization devices.*

Note: Items marked "*" are humanitarian demining technologies under development as part of this program.

MOBILE TRAINING SYSTEM

The Mobile Training System is a suite of multi-media audio-visual and computer equipment that provides mine awareness training. Effective training on mine recognition and what to do when encountering mines is a significant means to reduce casualties due to landmines. This mobile and multi-lingual mine awareness training facility trains indigenous personnel on mine awareness, safety procedures and what to do in certain situations. There are two versions of mine awareness trainers. A man-portable system fits into suitcases that trainers can hand carry to difficult to reach locations. There is a vehicle mounted version for more accessible areas.

PSS/12 MINE LOCATION MARKER

To increase the efficiency of mine detection and marking when using hand held detectors, this effort adds a marking device to the Army standard AN/PSS/12 detector. Currently, when a person operating the AN/PSS/12 locates a mine, he stops to position a marking item over the spot before continuing to detect. A trigger operated marking device, attached to the hand held detector, makes the marking process much more efficient.

BLAST AND FRAGMENT CONTAINERS

United States demining policy requires the destruction of landmines in place. However, this can be counterproductive if the explosion also destroys high value assets or critical facilities located close to the mine. The practice of placing mines very close to important facilities and augmenting them with anti-handling devices makes the need for a blast and fragment container extremely important. This effort demonstrated the effectiveness of a 27 inch diameter blast and fragment container that deminers place over a mine. Construction consists of single length S2 glass, which is dry rolled into a 1 inch thick cylindrical container weighing just under 85 pounds. The blast and fragment container vents the forces of the mine detonation upward and away from critical structures and contains the fragments caused by the mine detonation. This prevents the fragments from causing damage to these high value assets or critical structures.

BLAST PROTECTED VEHICLE (BPV)

The Blast Protected Vehicle system uses inexpensive off-the-shelf material to add anti-personnel mine protection to vehicles being used for humanitarian demining. This program evaluated flexible blast blankets mounted under the chassis and transparent armor to protect the vehicle from small AP blast and fragmentation mines. Another modification is the addition of an internal roll bar to protect occupants should a mine blast roll the vehicle. The roll bar also serves as an attachment point for a safety harness and a seat anchor. The blast blanket consists of Kevlar. Rigid glass fiber structures are also used. Chemically bonded ceramic cement with steel wire for reinforcement is in the front wheel wells and in the floor of the cab. The transparent armor is Lexan protective shield.

F. Other Items

VEHICLE TOWED ROLLER

Anti-personnel mine detonating rollers towable by commercial vehicles provide large area clearance.

III. CONTINUING TECHNOLOGY NEEDS

The Government's increased understanding of the serious economic and political implications to any nation with a severe landmine problem resulted in the establishment of a DoD led and funded research and development program for humanitarian demining technologies beginning in FY97. In addition, DoD recently created a UXO Clearance Executive Committee. This Committee is to ensure that there is a well-structured overall UXO clearance effort, and to act as a funnel to provide common policy guidance to all DoD activities working in this arena. The NVESD, in coordination with the UXO Clearance Executive Committee, with assistance from SOF components now involved in demining programs and with guidance from higher headquarters, will spearhead the new multi-year R&D program for humanitarian demining technologies.

There are a number of promising technologies that can enhance demining capabilities. For *individual mine detection*, the major technical challenge is discriminating landmines from metal debris - future efforts to improve detection will focus on providing a discrimination capability that includes the fusion of multi-sensor information and the incorporation of advanced signal processing techniques. In the area of *mine clearance*, cost-effective and efficient clearance techniques will be needed to clear landmines in all types of terrain. For *neutralization*, the challenge is to develop safe, reliable, and effective methods to eliminate the threat of individual mines without moving them - new technologies will be needed to economically and safely neutralize the latest mine threats. For *mine awareness and demining training systems*, the challenge is integration of the latest computer and training technologies, database links, and automated multi-lingual capabilities into a system that can be shared in an international environment.

Demining is far more comprehensive than combat mine clearance. Demining requires as close to 100 per cent destruction as possible. A description of equipment needs appears below. There are four major categories: Detection Systems, Mine Clearance Systems, Multi-media Support Systems and Individual Deminer Items.

A. Detection Systems

The capability to detect surface, buried and shallow water mines is critical to determine where mines are and are not. Deminers must be able to locate minefields and individual mines in all terrain. This will require a high degree of fusion of the output signals from various sensor types and configurations specialized for the terrain, weather and environment of the area. The following list describes the types of detection technologies of interest:

- Modular, sensor fused detection systems. Such systems could be ground based or mounted on fixed wing, lighter than air or rotary winged aircraft. Output must be viewable in real time, and as processed data for rapid analysis. The need for ground based detection systems includes vehicle or fixed-mast mounted quality assurance systems to locate minefields and mine-free terrain. Along with new ideas for aerial based sensor systems, the NVESD will examine the utility of the Airborne Standoff Minefield Detection System (ASTAMIDS) for demining. The ASTAMIDS is an ongoing Army countermine R&D program to detect mined areas from sensors mounted on an aerial platform.

- Systems that can provide visual image data from cameras on manned or unmanned platforms to search shallow water covered areas. These systems should find mines along riverbanks, shallow ponds, rice paddies and other areas where people would normally wade while carrying out their daily activities.

- Mine and ordnance detectors combined with precise position locators and transmitters for reporting, recording, and electronically marking mines, minefields and unexploded ordnance. With precise data on the location and composition of a mined area, clearing teams can proceed directly to a suspected location. These systems could use available data links to transmit new mine data directly to the support element responsible for data analysis. The hand-held marking system would allow predetermined messages and codes representing specific mission situations to be included in the transmission. This capability facilitates planning and it defines future clearance missions and near term mine awareness information for the local population, including where there are no mines.

- Bio-sensors, vapor collectors and element analysis systems to confirm the presence or absence of explosives. A monitoring system for hazardous and traceable chemicals from explosive compounds will be valuable in discovering small amounts of explosives. Examples of such systems are highly trained dog and handler teams and bio-chemical, optical or mechanical devices. These systems should be able to locate the approximate position of landmines, and more importantly to confirm the existence of explosive compounds associated with other sensor alerts.

- Physical marking and fencing of minefields and unexploded ordnance to warn soldier and civilian populations of potentially hazardous areas.

Infrared sensors, ground penetrating radar, pulsed induction mine detectors, miniature handheld mine detectors and hand held trip wire detectors are examples of technologies that have applicability in more than one of the above areas.

B. Mine Clearance Systems

- A means to remove mines from berms is important for humanitarian demining. It is critical for decision makers to understand that breaching and clearing a minefield to military standards, and demining are two very different actions even though they use similar technologies. Current military mechanical breaching equipment is not effective for humanitarian demining. This equipment moves and deposits the mines into a berm. Demining requires that there be no mine laden berm following area clearance. Berms also cover ground that may contain mines. Experience in the Kuwait clean-up effort proved that one of the more dangerous jobs in clearing mines is removing them from these berms. The design of new innovative devices to accomplish this task is mandatory, since the failure to do so will result in continued reliance on clearance by hand.

- Equipment that creates safe lanes through minefields to facilitate the start of demining operations. This equipment would either destroy the mines that they encounter, position them for manual destruction by follow-on deminers or a combination of both.

- Remotely controlled special purpose platforms such as mini-flails or mechanical diggers for detecting and breaching on-road and off-route anti-personnel mines. These platforms should be able to detect and activate simple pressure, trip wire and sensor activated anti-personnel mines. This equipment will also expose or move anti-personnel mines not activated or destroyed by the platform's neutralization mechanism. Heavy earth tilling machines will destroy any devices in its path by tearing them apart.

- Special purpose grapnels launched from vehicles to activate trip wire fuses, expose electronic mine activation links and cut tactical or electrical wire used to command detonate mines. These devices must be capable of operating in heavy grass and underbrush. They will be critical to establishing safe lanes in areas where deminers suspect the presence of trip wires or command detonated devices. They will also be the initial thrust areas where deminers suspect the presence of influence fuse activators. Their purpose is to dig up and cut the command wires between mine firing command modules and the mines. Employment of seismic sensors has already occurred in operational mine fields.

- Mechanical landmine destroyers or removal devices, such as plows, blades and rollers specialized for humanitarian demining. An important design consideration is that cleared areas must still be able to support agriculture. These devices in areas of open terrain to separate mines and other ordnance from earth and smaller debris. An additional need is for similar devices or kits for rugged terrain. These devices must be able to expose and mark mines and unexploded heavy ordnance without detonation. Follow-on personnel will destroy the uncovered items. These devices must allow tandem operation of two or more systems during breaching or demining operations where the terrain allows. Removing mines from berms is a particularly difficult task and requires heavy, robust systems able to meet the stress of daily use and of occasional detonations. These items should work with commercial horizontal construction equipment.

- Remotely controlled clearers capable of safely neutralizing, digging up and removing buried mines and other explosive devices equipped with anti-disturbance devices in close proximity to critical facilities. This machine would use foam or other suitable compounds to encapsulate sensitive explosive devices and remove them from high value areas.

- In-situ neutralization devices for easy and safe destruction of mines where deminers find them. Of special interest are explosive mine neutralization devices that are not practical for use as ammunition, and non-explosive chemical neutralization means.

C. Multi-media Support Systems

Mine awareness is one of the most significant factors in the reduction of landmine casualties. Multi-media hardware and software systems will greatly aid SOF demining trainers to educate host nation people and to establish demining training programs. Such systems must be robust, and must support many different languages and cultures.

- Interactive Mine/Countermine Databases will play an important part in mine awareness and in demining training. The main purpose of such databases is to support rapid mine

hardware analysis. This facilitates identification and training for host country demining cadres on the types of mines they are facing. It also provides mine awareness media for training the local population. Demining mission elements will deploy with computer, printing, and visual media projection capabilities. Group training and mine awareness training media may be in the form of mine database information displayed on a monitor, and by distribution of printed media such as posters, booklets and iron-on patterns for T-shirts. A database of worldwide countermine equipment will also provide for more effective mission planning. This database must have real-time capability for two-way communication between the technical support assets who sustain and keep the database up-to-date, SOF and their host country demining cadres.

- Portable, mobile training systems with hardware and software for the mine / countermine database and for the multi-media training support system described above. Such a system must have the ability to rapidly prepare mine awareness and deminer training media and information as leaflets, radio and television presentations, movie film and posters printed in the host country or in a common denominator language. In regions of low literacy, such systems should use descriptive photos and line drawings, instead of words, to describe all devices in the area and the dangers associated with them.

D. Individual Deminer Items

An important need is a "tool box" of specialized individual hand and power tools to make demining safer, faster and easier. A cart stocked with such items will greatly improve the demining process where the situation requires that it be performed manually. Specialized probes, light grapnels, long reach weed eaters and high power air jets are a few examples. This one system will increase coverage by at least ten times the current capability.

IV. Conclusion

Humanitarian demining requirements are vast and highly varied. The full range of Land Countermine, UXO Remediation, Battlefield UXO and explosive ordnance disposal activities includes detection, marking, reporting, recording, breaching, clearing, neutralization, destruction, training and mine awareness. These activities occur simultaneously and continually throughout the operation. No individual item can perform all of these functions. The demining community needs wide variety of low and high technology solutions in the field as soon as possible. The FY95 - FY96 program is a significant beginning to achieve this goal. A large part of the effort beginning in FY97 will build on the success of the progress made to date.

Demining is a very high visibility international effort. The Night Vision and Electronic Sensors Directorate engineers and scientists are working on new ideas for technological solutions, and are continuing to improve on promising alternatives developed to date. The NVESD welcomes assistance from all of our colleagues.

Command Communications Video & Light System (CCVLS)

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Abstract -- **This paper presents information on a self contained, rapid deployment audio and visual communications technology that is ideal for Humanitarian Demining in Operations Other Than War (OOTW) scenarios. Current policy does not allow US demining personnel to enter minefields. Therefore, communication between US personnel and host country deminers is vital for the overall efficiency of the demining mission and the safety of the individuals performing the demining mission. The Command Communications Video and Light System (CCVLS) is a state-of-the-art communications system that enables a deminer to transmit real time audio and video from a minefield to a command post located up to one mile line of sight (Fig. 1).**

I. INTRODUCTION

Antipersonnel (AP) and antitank (AT) landmines are a threat to US personnel both in combat and in Operations Other Than War (OOTW). The United States Department of State estimates that 80-110 million mines litter the world, the majority of which were deployed during the last 15 years. Various reports estimate that 150-500 people are killed or wounded every week throughout the world, mostly innocent civilians. Landmines prevent growth and development in emerging or rebuilding countries, impede repairs to infrastructure, disrupt humanitarian aid shipments and destroy the moral of the civilians living close to the minefields.

Landmines also effect the world's economy. It has been estimated that mines sometimes cost as much as $1,000 each to clear. This does not take into account the cost of treatment and rehabilitation for mine incident survivors or the training that is required for demining operations.

The world landmine problem is still getting worse. More mines are being laid than are cleared each year. The January 1994 issue of the New York Times Magazine stated that 340 types of mines are manufactured in 48 nations. Some of the makers are state owned and others are private manufacturers who traffic specifically in government contracts. It estimated that 10 -30 million mines are produced each year.



Figure 1. Command Communications Video and Light System (CCVLS)

That number should be decreasing thanks to numerous efforts by the United States and the United Nations (UN). The U.S. has formed the Interagency Working Group (IWG) on Demining and Landmine Control to coordinate and administer efforts in this area and has declared a moratorium on the export of antipersonnel landmines. A Demining Assistance Program has been established to initiate research and development into cost-effective demining techniques.

The Humanitarian Demining Team at the Night Vision and Electronic Sensors Directorate (NVESD) at Fort Belvoir has developed numerous technologies to support individual deminers and demining operations in Operations Other Than War (OOTW) scenarios. This paper describes a development effort that aids demining personnel in mine clearing operations and training procedures using a video and audio communications system.

This paper will also briefly discuss the U.S. policy that has led to the requirement and need for such a system. The Command Communications Video and Light System (CCVLS)

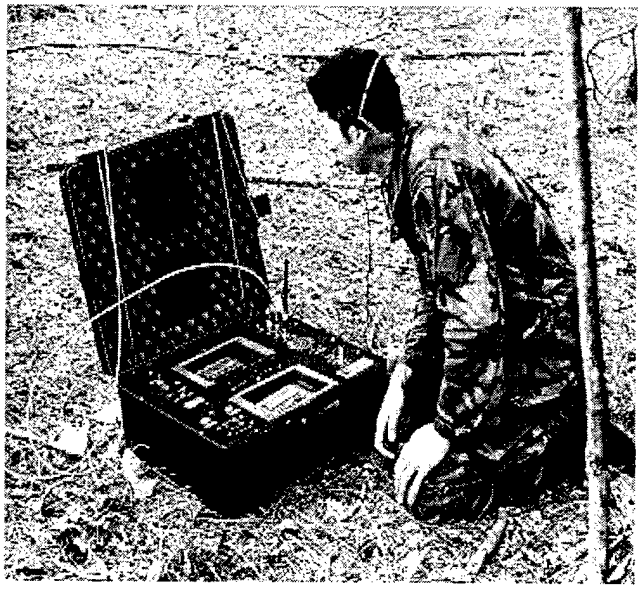


Figure 2. CCVLS provides audio and video communications to personnel located at command post

is a state-of-the-art communications system that enables a deminer to transmit real time audio and video from a minefield to a command post located in a safe area up to one mile line-of-sight (Fig. 2). Personnel located at the command post can monitor and record all activity in the minefield as well as provide instructions to the demining individual if required. The video can then be later used for training individual deminers or demining team on proper demining and safety procedures.

II. Overview of Requirement

The overall purpose of the Humanitarian Demining Program is to promote U.S. foreign policy by training indigenous personnel on demining procedures, the hazards associated with landmines and the safety associated with the task of demining. This purpose is to be achieved by developing a comprehensive approach to integrate equipment, technical data and support into the demining program.

U.S. troops perform live operations upon completion of the basic and advanced training programs and once the collective skills have been trained. Collective skills training brings units together as teams and establishes the Standard Operating Procedures (SOPs) for conducting live operations. U.S. troops do not perform demining for host nations. No U.S. Government personnel will be subjected to unreasonable risk nor will they enter active minefields. Host nation personnel will be trained by U.S. personnel on mine clearing operations and safety procedures and should be taught that whenever possible, mines will be destroyed in place with demolitions.



Figure 3. CCVLS is easy to transport and set up in the field

Because U.S. soldiers are not allowed to enter active minefields, equipment is required to aid U.S. personnel in performing their mission efficiently and safely. One such requirement is the need for audio and video communications between the host nation deminer and the U.S. soldier. Fulfillment of this need is critical for safety and training purposes.

III. System Description/Purpose

The Command Communications Video and Light System (CCVLS) is a rapidly deployable, self-contained video and audio communications system. It enables a deminer to communicate back to personnel located at a command postoutside the active minefield. The command post personnel can provide instructions, techniques and procedures, and warn the deminer of any safety issues associated with specific landmines. All this can be accomplished while recording all activity in the minefield from the deminer's a helmet mounted camera and a perimeter link camera.



Figure 4. SOF Deminer equipped with walk around unit and camera mounted on Protec helmet

CCVLS is comprised of a Protec helmet, two camera sources, high gain directional antennas and three easily transportable cases. One case contains the command post and the other two contain the deminer's down range and perimeter link components. A battery charger is contained in a fourth case, however this unit is not required at all times.

The deminer enters an active minefield wearing a miniature camera source mounted on a spectra composite armor Protec helmet and a belt containing the walk around unit (Fig. 4). The cameras are black and white, auto iris, fixed focus and mount to the deminer's helmet or face shield. The walk around unit contains a VHF FM receiver for audio communications, a boom microphone, 12 volt sealed lead acid battery and a low power S-Band 25 mW transmitter that sends audio and video signals to a down range unit located anywhere from 50 to 200 feet away. The walk around unit uses omni directional antennas and transmits video at 1765 MHz.



Figure 5. Down range unit receives signal from the walk around unit and restrnsmits signal to the command post

The down range unit is comprised of a single case containing a 1-Watt L-Band transmitter, S-Band receiver and internal and external power supplies (Fig. 5). Once the down range unit receives the signal from the deminer's walk around unit, it retransmits the signal to the command post via RF link. This signal can be transmitted up to one mile line-of-sight.

The perimeter link unit is comprised of a single case containing a 1-Watt L-Band transmitter and internal and external power supplies (Fig. 6). It also includes a miniature wide angle video camera that is positioned by the deminer in a safe zone outside the demining work area. This additional camera provides the personnel at the command post with a standoff view of the demining activity. The perimeter link unit transmits video directly to the command post.

The command post is comprised of two L-Band receivers, one 5-Watt VHF transmitter, two self contained color LCD monitors, two 8mm video tape recorders, a headset for audio communications, and internal and external power supplies (Fig. 7). walk around unit. This unit allows personnel outside the minefield to receive real time audio and video from the down range unit and perimeter link unit simultaneously. Personnel at the command post can communicate directly with the deminer via the walk around unit.



Figure 6. Perimeter link unit transmits video from a second camera source directly to the command post

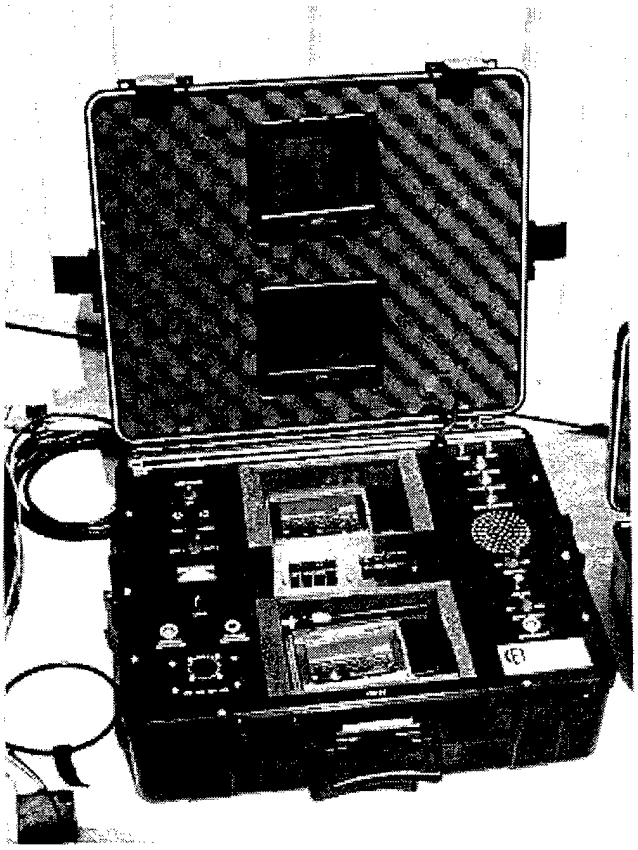


Figure 7. Command post unit is used to receive video from the minefield and transmit and receive audio to and from the deminer

As previously explained, the purpose of the CCVLS is to enable the deminer to transmit video and communicate with personnel located at a command post outside the active minefield so that he/she may receive instructions, techniques and procedures, and safety recommendations associated with the neutralization of specific landmines. In addition to the purpose of communication is the ability to record minefield activities that can later be used to train indigenous personnel in mine clearance operations.

CCVLS has been designed to be a low cost demining support system that is easy to transport, easy to operate and easy to maintain. The purpose of it's low cost design is so that U.S. military or possibly host nation countries could afford to purchase such items to support their demining operational needs. It must also be easy to operate as indigenous personnel will be required to operate the equipment once they have received the required training. Finally, the system must be easily maintained. Preventive maintenance should be trained as well as simple repair procedures. The system must be able to be sustained in the field.

IV. TEST & DEMONSTRATION RESULTS

The Humanitarian Demining Team conducted an initial Operational Capabilities Test & Demonstration (OCTD) in November 1995 at Fort A.P. Hill, Virginia. The Command Communications Video and Light System (CCVLS) was tested in various demining scenarios to determine: 1) it's effectiveness in assisting the deminer in locating and neutralizing landmines, 2) any human factors associated with the CCVLS equipment, 3) the effectiveness of the two-way radio communication, and 4) the quality of the video at the command post.

The CCVLS was effective in assisting the deminer locate mines in various environments and conditions using the helmet mounted camera source and the telescopic pole.

Two U.S. Special Operations Forces (SOF) personnel were trained on the CCVLS equipment and performed the entire test and demonstration. One played the role as the deminer in the field and the other performed the functions of the command post operator. Throughout testing, the SOF deminer wore the walk around unit and helmet mounted camera. The perimeter link camera source was set up in a safe zone approximately 75-100



Figure 8. SOF deminer performing mission testing with CCVLS during Operational Capabilities Testing and Demonstration at Fort A.P. Hill, VA

feet outside the demining work area. Standard demining equipment such as metal detectors, probes, and neutralization foams were used by the SOF deminer to support the demining test missions. The command post was set up in a tent approximately 200 meters outside the test areas.

The CCVLS equipment effectively assisted the deminer by providing video and audio via RF link to the command post. The SOF operator at the command post used both video sources and audio feedback from the deminer to monitor all activity in the minefield and to relay safety procedures and instructions when they were required. The SOF deminer proceeded to locate and neutralize various mines in different scenarios using the CCVLS equipment. The telescoping pole was also extremely effective at locating mines and/or trip wire devices around obstacles or underneath vehicles. There were no major human factor issues associated with the equipment. Training the SOF operators on the use of the CCVLS equipment went smoothly. The equipment was easy to set up and tear down and easily transportable to the field by two individuals. The only suggestion by the SOF operators was to integrate the helmet mounted camera source onto a Protec type helmet with a protective face shield and a chin strap.

The audio signal between the command post operator and the deminer was most often clear and intelligible at distances up to 1/2 mile line-of-sight. The video images received at the command post were most often clear and of high quality. The only problems that affected the audio or video communications occurred due to low battery life and/or extreme cold conditions. Some video interference occurred when the command post was set up behind large bunkers obstructing the line-of-sight RF transmission between the antennas.

In fiscal year 1996, the Humanitarian Demining Team made several modification improvements to the CCVLS equipment and performed follow-up testing in August 1996 at Fort A.P. Hill, Virginia.

Many modifications were made to the existing CCVLS equipment based on operator feedback from prior testing. First, high gain directional antennas replaced the omnidirectional antennas to improve the RF transmission between the walk around unit and the command post and between the perimeter link unit and the command post. All units were provided with replaceable/rechargeable lead acid battery packs in addition to their original 12 volt internal power source. Additionally, the command post may be operated indefinitely by using the supplied battery charger as a power source. The battery charger can be operated from either a 12VDC or 110VAC power supply. Third, a Protec Spectra Helmet with face shield, chin strap, internal speaker, and boom microphone replaced original helmet. Finally, the deminer now wears a soft nylon belt pack to hold the batteries and electronic walk around unit.

Again, the CCVLS was tested in various demining scenarios to determine if the improvements did indeed correct the minor problems that occurred during previous testing. The high gain directional antennas improved the RF transmission between the command post and the down range units. The system operated effectively at distances up to 3/4 miles line-of-sight without interference. Another significant advantage of having the tripod mounted high gain directional antennas was that the command post could now be set up inside trailers or behind bunkers because the antennas were no longer attached directly to the command post unit. The replaceable/rechargeable battery packs provided for continuous power and operation. The SOF deminer had back up batteries in his nylon belt that allowed him to simply switch the batteries on the walk around unit when they began to run low. The down range unit, the perimeter link unit and the command post were also equipped with back up batteries for continuous operation. Demining operations therefore, were uninterrupted. The rechargeable/replaceable batteries also contributed to excellent video quality received at the command post and clear audio communication between the deminer and the command post operator. The Protec helmet equipped with a protective face shield and chin strap provided the deminer with significantly more protection and comfort. SOF operators commented that the extra weight was offset by the extra comfort and assurance.

Overall, the second test was a great success. Each additional component that was integrated into the CCVLS system was proven to be valuable and contributed to the overall improvement of system performance and reliability.

V. CONCLUSIONS

Humanitarian Demining requires new technologies in areas of detection, clearance, neutralization and training. Because U.S. soldiers are not allowed to enter active minefields, technologies must be developed that the host nation's deminer can use to allow hands free operation while enhancing the overall efficiency and safety of the demining mission.

The Command Communications Video and Light System (CCVLS) is a communications system that allows hands free audio communication and video transmission to operators located at a command post outside the demining area. CCVLS is a low cost, easy to use, easy to maintain and easy to transport system that can support many different humanitarian demining missions immediately.

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Cooperation in Europe for Humanitarian Demining

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Abstract

It is difficult to have a clear view of all the activities in the field of demining that take place in Europe. Conferences are quite visible, but military projects are not. Nationally funded, industrial and private research are difficult to evaluate concerning their real support and hope for success. Nevertheless, it is clear that Europe is making a significant effort in favour of demining technologies, with several projects under way and a reasonable spirit for cooperation.

1. Introduction

Europe has developed a high sensitivity to the problem of antipersonnel mines. Accidents in the former Yugoslavia involving journalists have been reported in detail. During the Bosnia conflict, 3 millions mines have been laid close to the heart of Europe, in a charming country where many Europeans used to spend peaceful holidays.

The action of the NGOs before the Vienna Conference (Sept 95), which unhappily did not register any significant progress, drew also the attention of the political, economical and scientific community to the problem of land mines.

2. Conferences

The first humanitarian demining workshop was organized in 1993 by the CICR in Montreux [CICR93]. The problem was well stated, but only few technological aspects were considered.

The FOA (Swedish Defense Research Establishment) organized the following year a technical workshop in Stockholm [FOA94]. Several technologies were analyzed. Another meeting was organized in November 1994 in Ispra (Italy) [ISPRA94], including the initial proposal for a European project.

In 1995, the year of the first Monterey Conference [AV/MCM95], there were in Switzerland two consecutive conferences. The technical meeting in Lausanne [WAPM95] was a good complement to the major political and technical UN meeting in Geneva [UN95], attended by 3 to 10 delegates from each of 97 countries, plus governmental and non-governmental organizations.

The UN conference was repeated at Elsinore (Denmark) in July 1996 [UN96], without the political side (280 delegates from 47 countries). The evolution in one year showed positive and negative aspects: deminers have improved their SOP (Standard Operation Procedures) and are more open to different solutions (toolbox approach). But the projects for new sensor systems, announced in Geneva, are still in their starting phase.

The ISMCR Conference on Measurement and Control in Robotics [ISMCR96] included two keynote speeches and a special session on mine clearance. The public was however not really receptive to humanitarian demining, since the conference topic concerned mainly control. The MD'96 conference [MD96], which took place in Edinburgh early October 1996, can be considered to be the first

scientific conference devoted to humanitarian demining; unfortunately it was restricted to sensor technologies, with too many "academic" papers. There were 180 participants from Europe and the rest of the world, including the very active Australia.

3. Projects

A. Military

Military projects are of course not well known, and never give a high priority to real humanitarian demining. France, UK, Germany, and Israel have the most important programs. Swedish research is the most visible, since the FOA (Swedish Defense Research Establishment) has a clear interest in humanitarian demining. The FOA announces its projects and demonstrates in public its working prototypes: at the Montreux Symposium [CICR93], original odor sensor approaches were presented, which were later discontinued. In Geneva [UN95], a man-portable combined metal detector - ground penetrating radar - odour sensor was announced. Its development, however, did not start as soon as expected, and it is underway now without the odor sensor. The FOA works together with Bofors, a private company producing military equipment, which demonstrated a motorized roller that digs up to 50cm in the soil, and breaks antipersonnel and antitank mines into pieces if they do not detonate (the roller survives to 12 kg of explosives). A Leopard tanks equipped with one of these rollers has been sent recently to Bosnia; results will be interesting to know. In Elsinore [UN96] and Edinburgh [MD96], Bofors presented its odor sensor project, with still several unsolved issued.

ELTA Electronic, Israel, has been developing for several years a vehicle-mounted array of GPR sensors. The application is primarily for detecting anti-tank mines at a speed of 4 km/h, and it interests very much some armies.

B. European Community

Since 1994, Dr. Linkohr from the European Parliament influenced the German government and the EU community :

1) to execute a study (done at the Joint Research Center in Ispra) [ISPRA94] on the state of knowledge in Europe;
2) to recommend a Ecu 50 Mio ($ 65 Mio) R&D programme to be launched by the EC and managed by the JRC. The solution must be achieved by teams working exclusively in the civilian domain.

A call for a prestudy has been launched in summer 96 and triggered a wide interest. A dozen of groups of partners have answered the call, showing a considerable interest. The call for proposal should be followed, in early 1997, by the last set of calls of the 4th framework program. Due to restrictions in this program, it is probable that only Ecu 20 Mio will be avaliable for a development to be finished in 1998. Some details have been announced by the JRC: a vehicle carries an extended arm (10 metres) with an array of sensors at its end; sensor fusion and interpretation of data is performed between 3 selected sensors (GPR, induction gradiometer, polarimetric infrared sensor). Geographical Information Systems, soil parameters data bases, signature catalogs for relevant mines, working groups with similar programs in USA and Japan, and coordination with NGOs are also mentionned.

The role of the JRC is however not very clear. It claims to be a center of excellence, ready to help and coordinate European projects, but JRC is also answering to the call for project, the definition of which it has strongly influenced. The EC executives clearly would like to see the JRC doing the project.

C. National projects

Several national projects are known. We list only the ones which are not influenced by their military funding toward breaching and detection of anti-tank mines.

The Belgian Defense Ministry is supporting partners from 6 Belgian universities, the Royal Military Academy and the Belgian Demining Service, which operates also in Cambodia and Bosnia. Funds amount to $ 400.000 for 5 years. Working groups will develop sensors, algorithms and robots.

In Denmark, CAT (Centre for Advanced Technology) manages a project for a multisensor detection system, including GPR, carried by a vehicle.

Projects developed after the initiative of individuals do also exist. At the University of Edinburg, Prof S.H. Salter received recently about $ 30.000 from the Royal Academy of Engineering and from the Endinburgh Council for building the Dervish, an original mechanical device (fig 1). Tests on the mechanical frame with 10 kg of plastic explosive have already been made. Further financing should allow to send 3 prototypes to Angola.

In Switzerland, the DeTeC group (Demining Technology Center) is supported by ProVictimis and the goverment for a 2-year program that will allow to test on the field a combined GPR and metal detector system [Nicoud96]. The initial objective was to have a sensor carried by the Pemex robot, but it is difficult to propose a robot to replace a Cambodian deminer paid less than $ 1000 a year, his family receiving $ 5000 in case of accident.

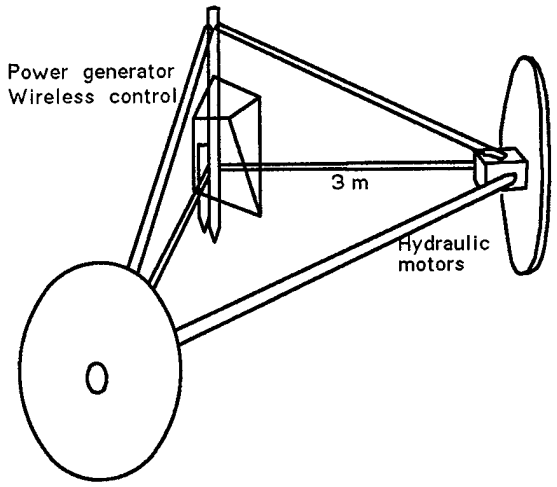


Fig. 1 The Dervish (200 kg)

D. Industrial projects

Successful metal detector companies like Foerster (Germany) and Schiebel (Austria), are active in developing new concepts, partly under contract with military and industrial partners. Foerster is pursuing the development of the ODIS rotating sensor concept [WAPM95], which DASA-Dornier has developed in 94-95 (fig 2).

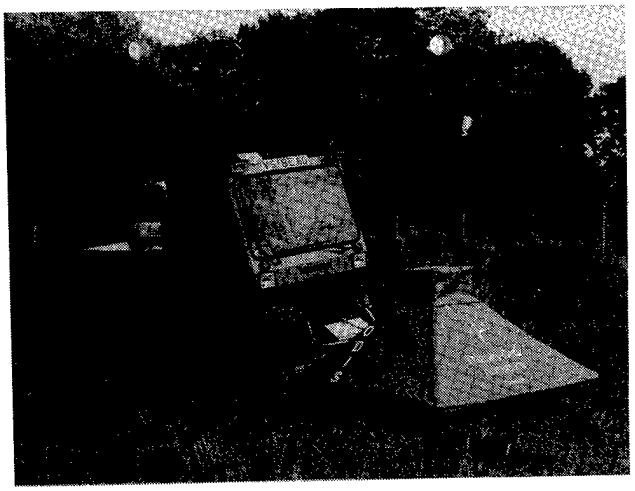


Fig. 2 The ODIS sensor carried by an Unimog

In England, ERA and EMRAD are GPR manufacturers, very concerned about landmine detection.

In France, SATIMO has developed interesting microwave imaging systems, applicable to AT mines. SATIMO is a spin-off of Supelec, an engineering school near Paris, where tomographic and

simulation algorithms have been developed, as well as at Nice University.

Walter Krohn in Germany has privately realized a mechanical engine similar to Bofors' motorized roller, developed initially to convert the forest soil into agricultural lands. Two such machines have been tested in Mozambique in August 95, with the support of the German government. 6400 mines have been neutralized over 56 Ha, during a 5-month campaign with a team of 16.

Industry is interested in carrying out projects and investing on demining technology. But when the problem is explained to them in an honest way, and if there is no military background interest, they are discouraged by the low probability for return on investment.

Many researchers are interested in working on demining projects, but specific financing mechanisms do not exist. Projects are started on the initiative of researchers with the support of their company, local NGOs and in some cases government funds. A good level of cooperation exists between teams from different countries, but researchers only recently discovered their common interest, frequently through the Web. The Internet is a powerfull tool for cooperation between scientists, both for discovering partners of common interest, and for exchanging recent publications and results.

E. International Coordination

It was emphasized at the Geneva and Elsinore UN conferences that research into demining technologies is taking place in many countries, usually under army contracts. Unfortunately, there is overlap, duplication, lack of communication, and competition. Besides the few scientific workshops, there is no mechanism for drawing together the researchers to achieve collaboration. To get the best result from the scattered resources available, research needs to be coordinated, at national level first, but international collaboration should be promoted, possibly using the United Nations as a forum or catalyst. The problem is that the UN has no money for doing such a work.

The major difficulty the researchers and the industry will be faced with is how to test the new equipment, given that any error may cause an expensive accident and will stop further financing. Proposed solutions have to be certified before being accepted by demining organization. Most products now do their final tests and fine tuning within the first customers. This is not possible with demining equipments.

There is a clear need for an international center working in relation with test facilities at DRA, FOA, JRC, test fields outside Europe, and on real mine fields in order to :

- make the information on updated current researches more easily accessible;
- make the tests on simulated and real mine fields easier;
- evaluate the proposed solutions, claimed to be ready for use by demining teams. This should be made by a neutral organism having the confidence of the UN, of the NGO supporting demining activities and of the demining organizations (CMAC, MAG, NPA, etc.);
- support financially either the companies building high technology demining equipments or the demining teams, in order to obtain the initially too expensive equipments being used for real demining.

4. Conclusion

It is time for the political and scientific community to increase its commitment in developing technological solutions for humanitarian demining. Besides the social and scientific value, economical justifications can be found, for the benefit of the countries plagued with mines, and for the selfish interest of developed countries providing equipment and getting control of new technologies applicable to

other fields.

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Post-conflict and sustainable humanitarian demining

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1 Introduction

Industry and research, previously supported by military funding are currantly quite interested in the developement of there activities toward humanitarian demining. Warfare money is decreasing, and the media have focused the public attention on the major problem created by antipersonnel landmines. Research and development are, to a certain extent, easier to obtain funding for, when the "humanitarian demining" label can be used. The nature of the research is however quite different when initiated by the army, by the UN, or by a country which, plagued by mines, is trying to peacefully recover its economy.

There are three phases of mine use, during and after a conflict, which will remain as long as antipersonnel mines are not banned.

Phase one: During the war, the armies protect their strategic positions with antitank and antipersonnel mines. The opponent's activity is to breach into these minefields, regardless of the material and human losses. We will not come back on these mine warfare aspects.

Phase two: When the conflict is over, Koweit being an exception, the country is economically ruined and the United Nation calls for the help of the armies of goodwill nations, in order to re-establish the communications, remove the anti-tank mines from the roads, delimit the minefields in which antipersonnel mines and unexploded ordnances could be found. This very usefull, but expensive activity, requires trained people and special equipments. In general, the objective is to get the local army trained for overtaking this work as soon as possible, with of course much more limited resources. This has happened in Cambodia 5 years ago, and is happening now in Bosnia. It is called humanitarian demining, but we will refer to it "post-conflict demining" in order to avoid the confusion with the third phase.

Phase 3: When the UN removes its support after 2 or 3 years, e.g. as in Cambodia (Afganistan, Angola, Mozambique are or will be similar), the economy is still completely down, the government has severe financial problems. Many people are killed or maimed everyday by antipersonnel mines without any compensation. Non profit demining organizations, supported by the UN and several NGOs (non governmental organisations), start to train the cheap local deminers in proding the ground patiently in order to find all the mines. In Cambodia, at the presend rate, it may take more than 100 years. This is sustainable humanitarian demining.

2 Post-conflict demining

The equipment used by the UN and the armies are quite traditional: armored vehicles carry the expatriate personnel, and teleoperated tanks pushing rollers trigger the explosion of anti-tank and anti-personnel mines laid on roads [1]. The exception is the US army which has a special requirement that the US soldiers are not allowed to walk on an active minefield. The "CNN" effect (any accident will be amplified by the media), gives a tremendous importance to the life of a soldier, and motivates the development and use of very expensive equipments, which no other country could afford.

An important amount of research funding, worth about 40 Mio dollars last year, has been spent for the development of technological solutions related to post-conflict demining, with the beleif that the ultimate solutions will soon be available, if sufficient funding for R&D is given. Many projects for teleoperated or autonomous robots, cameras, sensors, airborne detection systems which can only recognize anti-tank mines are developed by engineers who have not even seen a real mine-field. The objective appear to be to make a demonstration on some military test field, and get the project continued. From humanitarian deminers' view point, this is a complete waste of money.

3 NGO-supported humanitarian demining

A major concern of the NGOs is the health, food, education and economic problems of the many defavorised countries of the world. They are also concerned with the antipersonnel mine problem. They provide medical care and prothesis, or pay for the demining activities. In Cambodia, the CMAC (Cambodian Mine Action Centre) has 1800 deminers. Together with 4 other mine clearance organizations (800 additional deminers), they have cleared about 50 km2 in 4 years and removed less than 2% of the estimated number of mines in Cambodia.

The cost of a typical 1 year campaign with a platoon of 40 deminers is about 350,000 dollars. The result is a cleared area of about 70,000 square meters (5 soccer playgrounds) with 1 to 2 thousand of mines and UXOs removed. In a typical campaign, about 10% of the cost is payed to the expatriate specialists, 25% to the 100 time more numerous local deminers, 25% allows to buy the metal detectors and other tools, 25% is required for the vehicles, radios and computers, and the remaining 15% is for the running costs and administration.

4 Humanitarian demining operations in Cambodia

The technique for removing all mines from a minefield has not changed since World War II. A better definition of the procedures and a careful training of the deminers has significantly reduced the number of accidents over the last few years. These so called Standard Operation Procedures (SOPs) specify how to organize the work and security on the site. Groups of 2 or 3 deminers progress in 1 meter wide lanes distant by 20 meters (figure 1). Only one man at a time is in the dangerous area, wearing helmet and west shield; the other deminers stay 20 meters behind.

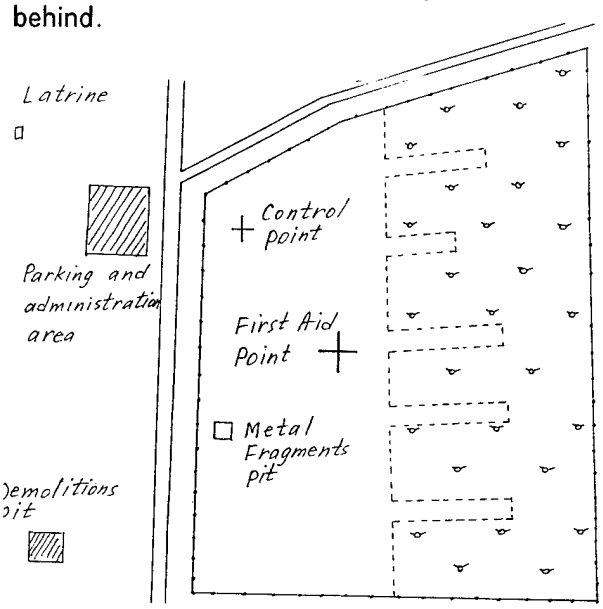


Fig 1: Layout of the penetration in a minefield

The work proceeds according to 4 operations, performed by the same deminer for 30 minutes, or by alternating specialized deminers.

1) Trip wire test. A 1 meter stick is carefully lifted through the high grass.

2) Vegetation removal. A 40 cm long area is cleared, trees under 20mm in diameter are cut.

3) Metal detector scanning. The correct functionning of the detector on a test piece is checked, and then the width of the lane, plus its sides are slowly scanned (fig 1). If an alarm occurs, a "hat" (20 cm diameter cone) is placed centered on the spot (or 20 cm in front depending on the procedure). If there is no alarm, the delimiting stick is moved 40cm forward, the side tapes are adjusted and the procedure continues with step 1.

4) Prodding the ground. The prodder, a 30cm sharp steel rod, is gently pushed

into the ground, the maximum angle of prodding being 30 degrees. Several actions every 2 cm in the direction of the spot allow to define the shape of the object. With the aid of a towel, the earth is removed and placed in a sand bag (some metal debris may be inside and have to be removed). The side of a large enough object is cleaned with a brush, waiting for inspection by the section commander. If it is a mine or UXO, the team starts a new line, and the object will be destroyed by a 200 g explosive charge at the next break. Some deminers prefer to unfuse the mine immediately, with the advantage the ground will not be disturbed by the explosion, no new additional pieces of metal being spread onto the field.

5 Need for adequate technologies

Humanitarian demining teams are open to new technologies, but they must fit their needs. CMAC is ready to do experiments on their training field near Phnom Penh, and later on real mine fields. Thirteen metal detectors have been evaluated in summer 96, dogs and the Bofors demining vehicle [2] will be tested in winter 96/97 with the support of the Swedish government.

What deminers however need in priority is a better mine sensor, able to distinguish between a metallic debris and a mine. Its cost must be low enough. Let us assume that the sensor is 5 times more expensive (reasonable guess if the additional sensor is a ground penetrating radar, the only available technology now). Looking at the figures given in section 3, this means that the cost of the campaign will double. Hence, the demining speed should at least double to make the solution acceptable. But since more than 50% of the time is spent in removing vegetation, it is just impossible.

The idea to use a robot for replacing the men doing this dangerous work brings the same cost/effectiveness issues. A deminer is paid $100 a month and his family gets $5000 in case of an accident. Replacing these deminers by robots brings also a social and economic problem: will they find other equally well paid jobs ?

Let us however mention the four design options for a demining vehicle or robot.

Existing vehicles used for war and post-conflict demining are teleoperated heavy tanks pushing a roller or a flail. US Army used 7 tele-operated M60 tanks pushing rollers in Bosnia [1]. The Bofors roller belongs to that category. These vehicles are designed to withstand anti-tank mines, that is 12 kg of explosives. They cannot be brought easily to the field, due to the poor conditions of roads and bridges, and will destroy most of the surviving irrigation structure. The mini-flail [3] is the only known small size (1 ton) teleoperated vehicle designed to withstand only 80 grams of explosive of an anti-personnel mine. Several vehicles have been proposed for moving an array of sensors (metal detector, GPR) over a road that may contain anti-tank mines; the VAMIDS project in US uses the Schiebel metal detector array, the ELTA (Israel) vehicle carries an array of GPRs.

The Pemex has been designed as a lightweight autonomous robot for searching antipersonnel mines [4]. The pressure on the ground, 5 kg, should not trigger the mines. The sensor head oscillates under the alternating movement of the wheels, in order to scan a width of about 1.2 meters. The project is suspended until an adequate sensor, weigthing less than 4 kg, can be installed inside the head.

The Lemming [5] has also been proposed for exploring minefields. Its smaller size brings more constraints to the sensor, but it may navigate correctly in some dense vegetation, with however the difficulty to explore systematically every square inch of the area. Robots with a snake-like shape have been proposed [6]. They would be better in dense vegetation, but where to put the sensors?

The vegetation problem needs substantially more attention of the researchers and the funding agencies. HALO Trust has developed and tested in Cambodia and Afganistan a $40,000 vegetation cutter which they claim to be cost-effective. It requires a free safe space next to the field. For insertion within the above

described SOP, a light-weight, man-operated, seed cutter could be of interest. It should not exercise pressure on the ground, and its maximum cost will depend on its efficiency, bearing in mind that the man-equivalent time saved is paid less than $1000 per year.

The third major problem humanitarian demining is faced with is getting the precise boundaries of suspected mine fields. Dogs, as successfully used by Mechem in South Africa are one solution. Proposals with expensive infrared and microwave devices embarked on a plane or helicopter have been partly demonstrated only for clear land (no vegetation) with big anti-tank mines recently buried. If odor sensors develop correctly over the next years, there is some hope that an autonomous small and reasonably cheap robot could explore every square meter of an area and come to the conclusion that there are no mines in it. This would be a real major progress.

6 Financing scenarios

It is clear that demining operations are too slow. Hundreds of years will be required for removing existing mines at the present pace. We need more money for removing mines on the field, but just increasing the amount given to demining organizations, without working on the technology, will reduce the number of innocent victims (10,000 civilians per year), but will not reduce the number of maimed deminers (1 for about 2000 mines). We need technology to both reduce the number of accidents and increase the productivity of demining teams. If the amount of money given by the international community doubles every year up to a factor ten, and if 25% of that money is devoted to a research centered on the needs of the deminers, the present manual demining activities will benefit from an immediate increase, and will have access to improved sensors and equipment, within 2-3 years [7]. Since any new technology is expensive as long the quantities have not ramped up, it will be necessary to subsidize the products for some time. Another part of the problem will be to qualify and test the prototypes: the support of an adequate neutral organization will be required.

7 Conclusion

Important amounts of money are devoted to projects related to post-conflict demining, but they do not bring what deminers on the field expect. A better understanding of their needs, obtained by visiting these teams and making early tests on real mine fields with the people able to continue to operate the proposed equipments is essential. Certification of the proposed products will be a long and serious process that should be considered from the beginning of the project.

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Minefield Proofing and Route Clearing in Bosnia Using Unmanned Ground Vehicles and the Standardized Teleoperation System

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Abstract - This paper will discuss the details of the minefield proofing and route clearing effort undertaken in Bosnia Herzegovina using Unmanned Ground Vehicles (UGV) and the Standardized Teleoperation System. This effort was sponsored and coordinated by the Unmanned Ground Vehicles/Systems Joint Program Office, and utilized 7 M60 tanks with rollers for proofing. Additional information will also be given on the Standardized Teleoperation System developed by Omnitech Robotics, Inc. and other UGV applications including previous and ongoing countermine systems installed on D7G dozers, HMMWVs and M1 main battle tanks.

I. Background

In October of 1995 the Office of the Deputy Chief of Staff Operations, United States Army Europe requested that the Unmanned Ground Vehicles/Systems Joint Project Office (UGV/S JPO) upgrade seven Panthers (turret-less M-60 tanks with mine rollers) with the Standardized Teleoperation System (STS) for countermine operations in Bosnia Herzegovina in support of Operation Joint Endeavor. The STS is a state-of-the-art teleoperation system which allows operators to control vehicles from a safe distance during hazardous operations. An Integrated Product Team - "Team Panther" was formed to tackle this urgent and potentially dangerous problem. Team members included representatives from the United States Army Engineer School (user and countermine instructors), Omnitech Robotics Incorporated (STS contractor), the United States Army Missile Command (technical/logistical assistance), 59th Ordinance Battalion (maintenance team members), and the UGV/S JPO (team leadership).

II. "The Panther"

The Panther is a turret-less M-60A3 tank equipped with track width mine clearing rollers. Fig. 1 illustrates a Panther with mine rollers attached. It is used to proof suspected mined fields that have been cleared by Combat Engineers and/or former warring factions in Bosnia. The Panther was originally outfitted with a previous generation remote control system through a contract administered by the UGV/S JPO as an interim measure until the next generation STS teleoperation controls for the Panther could be designed, produced, tested and fielded.

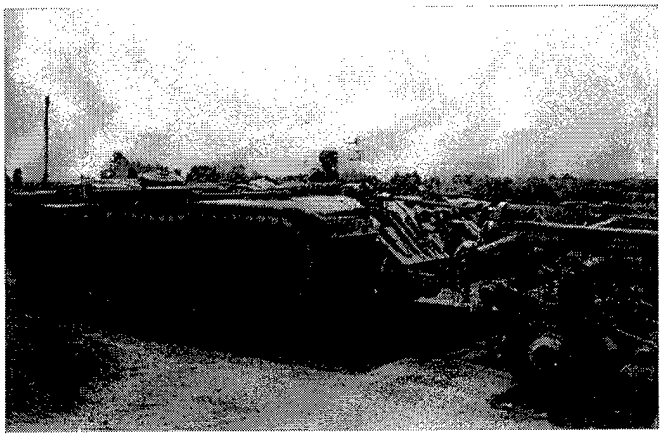


Fig. 1: A "Panther" system consists of a turret-less M60 tank with mine rollers and the STS for teleoperated control.

III. The Standardized Teleoperation System

The STS is a modular kit of components which can be added to any vehicle to convert it to teleoperated control (remote control with real-time video and audio feedback). The major components of the STS kit are shown in Fig. 2. They consist of the Operator Control Unit (OCU), Vehicle Control Unit

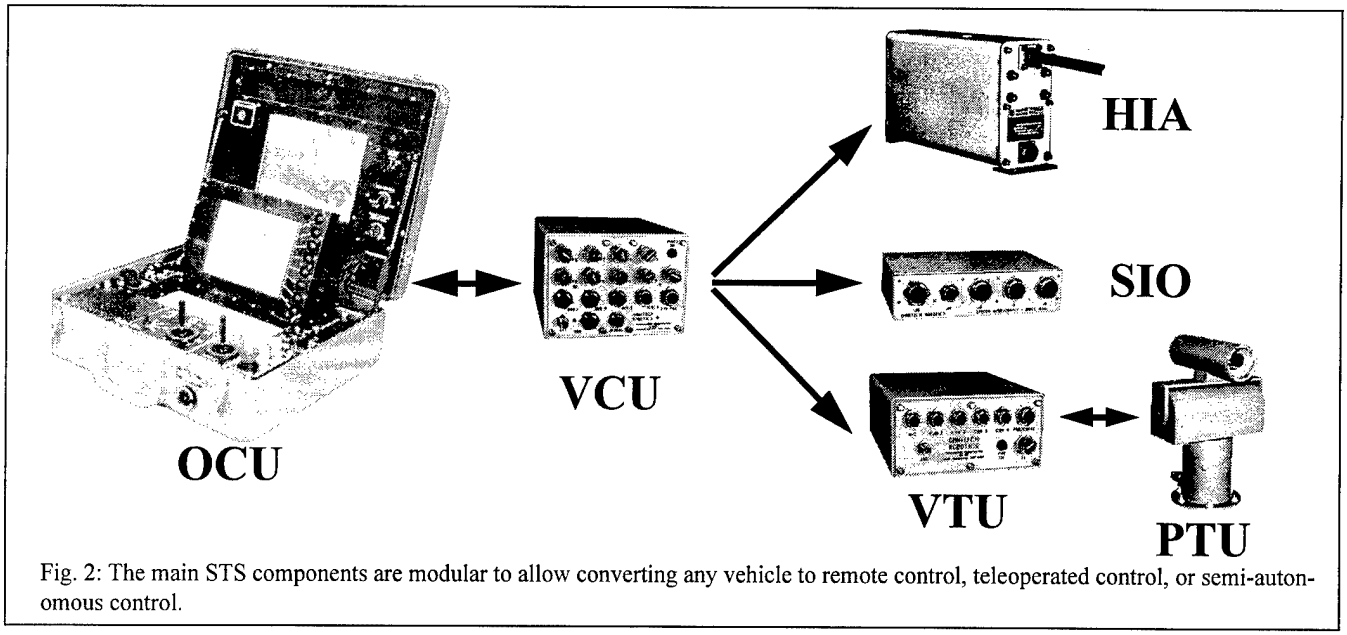


Fig. 2: The main STS components are modular to allow converting any vehicle to remote control, teleoperated control, or semi-autonomous control.

(VCU), High Integration Actuators (HIA), System Input/Output (SIO), Video Transmitter Unit (VTU) and Pan/Tilt Unit (PTU). Additional components are also available for autonomous control (GPS/INS based navigation), safety radio systems, and mission and payload specific interfaces like clear lane marking system control, Mine Clearing Line Charge (MICLIC) control, mine detector control, etc. The STS uses a serial control bus called Controller Area Network to provide scaleability of the design, allowing as few or as many components (HIA, SIO, VTU, etc.) as desired to be controlled by the OCU and VCU.

One key feature offered by the STS is the ability to change instantaneously from a manned mode to teleoperated mode with the flip of a single switch, thus maintaining the conventional manned capability while offering the advantages of teleoperation when desired. This allows commanders to take the Soldier or Marine out of harms way during hazardous operations using teleoperation, while not affecting mission convenience or reliability since the manned mode is always available. The STS increases force survivability by reducing loss of life and increasing system survivability during dangerous operations. Additionally the STS enhances mission performance by eliminating the operators stress caused by danger, allowing Soldiers and Marines to make clear and well thought out decisions in a safe, protected environment.

IV. From Concept to Reality

Prior to the "Team Panther" effort, the STS had been proven in Advanced Concept Technology Demonstrations (ACTD) and Advanced Warfighting Experiments (AWE) on multiple D7G dozers, M1 main battle tank chassis, and HMMWVs.

The challenge for "Team Panther" was to leverage this experience to meet the needs of combat engineers in real world operations in Bosnia Herzegovina for proofing mined fields and roads. To assure user satisfaction, high system reliability and rapid fielding were top priorities.

Leveraging success from a Small Business Innovation Research (SBIR) contract with Omnitech Robotics, Inc. for the development of the original STS, and under the direction of the UGV/S JPO led Integrated Product Team, the teleoperated Panther went from concept to reality in less than 7 months. This resulted in the fielding of nine STS kits for converting the seven M60 Panthers with mine rollers already in Bosnia, including two spare kits. Subsequently additional kits and spares have also been supplied.

The IPT team used their combined talents to define, plan, execute and manage the project while meeting user requirements. This included incorporation of system and programmatic upgrades derived from suggestions and feedback obtained from various users while conducting previous ACTD and AWE efforts. Some of the upgrades include:

- High brightness (daylight viewable) video and status displays were incorporated
- Minimal vehicle integration time was obtained by using pre-assembled STS "packs" that were dropped into place in the M60 tank turret
- High reliability of the system design was enhanced by performing environmental testing of two operational systems at Aberdeen Proving Grounds, including EMI, temperature, humidity, vibration, and rain testing of the systems. Lessons learned were incorporated in the production units
- High reliability of the system design was enhanced by requiring 40 contiguous hours of operational testing using army test per-

sonnel in a realistic scenario at the US Army Engineering School at Fort Leonard Wood, MO on their robotic vehicle test track (RTIA)

- High reliability of each unit was enhanced by mandating 72 hour burn in testing of each completed system
- High reliability of each unit was enhanced by including Built In Testing (BIT) in the system components to assist in fault detection, isolation, and recovery
- The Operator Control Unit (OCU) was reduced in volume by 57%, and in weight by 33% from the previous version to enhance user portability
- Arrangement and spacing of the OCU control inputs and display feedback were optimized based on human factors testing and reviews to meet military specifications
- Operator and Maintenance manuals were prepared to assist users in the field
- A Mobile Training Team consisting of three specially trained US Army Engineers, was formed to train users in Bosnia
- A Forward Support Team, consisting of three specially trained US Army personnel was formed to provide ongoing maintenance support of the Panther systems in Bosnia

V. Supporting Operation Joint Endeavor

In June 1996, the UGV/S JPO along with the USAES and Omnitech Robotics, Inc. dispatched an 11 man Team to Bosnia to install, train and maintain the STS on the Panther. This team is shown in Fig. 3. The team deployed to Bosnia and traveled to seven different companies in the 16th, 23rd and 40th Combat Engineer Battalions located throughout the American sector in Bosnia.

In order to install the seven STS kits in the Panther vehicles as soon as possible, the 11 man team would travel for one day, install an STS kit for one day (7 to 10 hours typical), and train user personnel for one day, then repeat the cycle for the next company. Transportation within Bosnia was provided by US Army transport convoys consisting of HMMWVs, 5 ton transports, and other material transport vehicles. Fig. 4 shows a photograph of two STS kits in their individual crates being transported by a material transport vehicle.

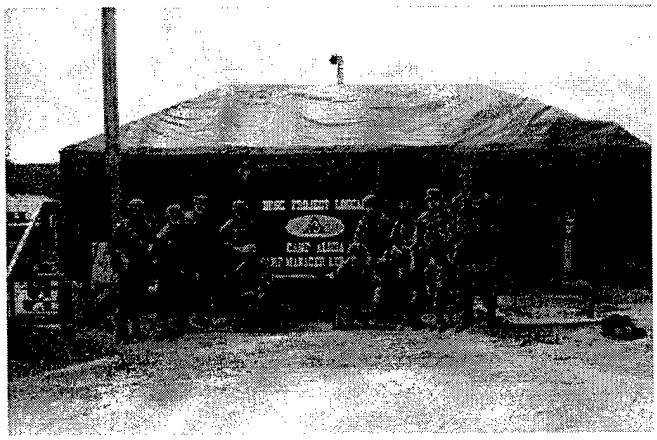


Fig. 3: The Bosnia support team for "Team Panther."



Fig. 4: Transportation within Bosnia was via military convoys, including supplies like these individually crated STS kits.

Fig. 5 shows a photograph of an STS pack being installed in an M60 Panther (the STS pack is the group of white boxes located in the rear-center of the M60 turret opening). The STS pack was removed from its individual crate, and set in place on the floor of the M60 tank using the transport vehicle's crane (or a Combat Engineering Vehicle's crane). Completion of the installation consisted of securing the pack, attaching the pre-fabricated push/pull cables and mechanisms, mounting the video cameras and covers, and connecting the electrical cables and connectors to the tank's electrical system. Finally calibration of the servo actuators was performed, and testing of the system was conducted to verify proper operation. This entire process took between seven and ten hours using four to six personnel.

A total of 34 soldiers from seven companies were trained to operate the STS. Fig. 6 shows a photograph of a group of combat engineers being trained in the field on operation of the

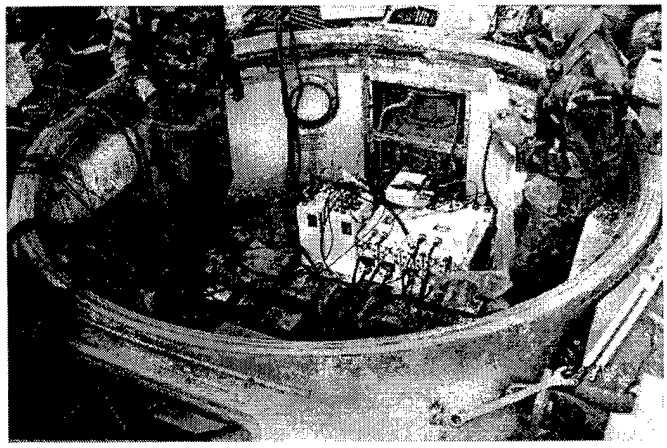


Fig. 5: The STS pack is mounted in the turret of the M60 Panther. It controls the vehicle with five push/pull cables and several electrical connectors.



Fig. 6: Field training of combat engineers was performed by US Army engineer personnel from the Engineering School at Ft. Leonard Wood, MO

Panther systems. Fig. 7 shows a photograph of a combat engineer performing a mine field proofing operation from the front passenger's seat of a HMMWV. The simple and accurate proportional controls of the STS, combined with bright, easy to see video and status displays helped users to catch on quickly to driving by teleoperated control. Although the OCUs were originally intended to be mounted in an M113 armored personnel carrier, in Bosnia the users requested that the OCUs be set up in the front seat of HMMWVs or inside the turret of Combat Engineering Vehicles (CEV). Fig. 8 shows a photograph of the M60 Panther with mine rollers proofing a suspected mine field.



Fig. 7: Operation of the Panther was performed by combat engineers using an Operator Control Unit mounted in a HMMWV, CEV, or M113 APC

The soldier's response to the new STS was overwhelmingly positive. On 29 June 1996, the 23 engineering battalion, "A" company, detonated an anti-tank mine during mine proofing operations. While the tank sustained damage, the STS continued to operate. Fig. 9 shows a photograph of the M60 tank on a transport vehicle after hitting the mine. Notice that the first road wheel and the track has been blown off. It is suspected

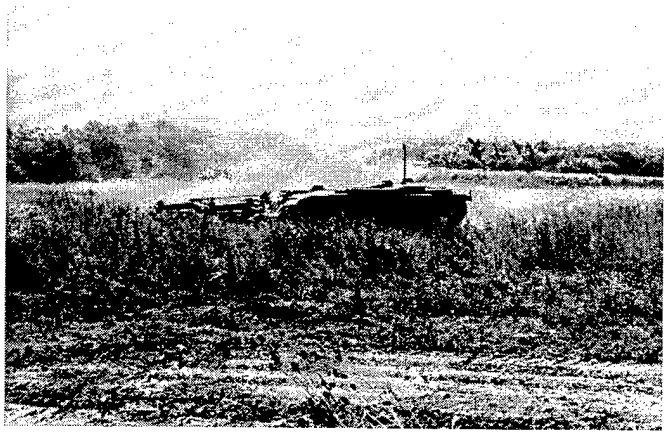


Fig. 8: The Panther in action - proofing a suspected mine field with the track width mine roller



Fig. 9: After hitting an anti-tank mine, this panther sustained a damaged track and first road wheel. Here is the Panther on a transport vehicle awaiting repair.

that the mine rollers failed to protect the tank treads and road wheel due to the fact that the rollers caster side to side excessively when the tank is turned sharply. The Panther has been proven on 3 other occasions so far, detonating anti-personnel and anti-tank mines that would have otherwise injured or killed U.S. soldiers or civilians. In all instances the Panther has accomplished its mission - detonating land mines while keeping our soldiers out of harms way.

VI. Other STS Applications

A. Interim Vehicle Mounted Mine Detector

The Interim Vehicle Mounted Mine Detector (IVMMD) is a joint initiative with the PM Mine/Countermine Office and UGV/S JPO. Omnitech was directed to prepare four teleoperated High Mobility Multipurpose Wheeled Vehicles (HMMWV) equipped with mine detectors. Alternative vehicles are also possible. Presently, the first two HMMWV vehicles have been teleoperated and are awaiting payload

integration.

This system uses two mine detector techniques, a magnetic mine detector antenna in front of the vehicle that is swept by the vehicle motion at a velocity ranging from 0.5 to 1 m.p.h., and a thermal imaging camera (FLIR) looking in front of the vehicle to detect mines using their thermal signature.

The STS installation for the HMMWV (Model M966, Truck, Utility: TOW Carrier, 1-1/4 Ton, 4x4) is compact, using only the passengers seat area behind the drivers seat to mount the STS equipment, as seen in Fig. 10. To automate the speed control of the vehicle, a new feature was added to the STS implementing a "cruise control" for automatic speed regulation of the HMMWV at low speed. Speed regulation between 0.5 to 1 m.p.h. nominal was required to assure the mine detector and operator could detect a mine then stop the vehicle prior to driving over the mine and potentially detonating it. This capability has been successfully demonstrated on two HMMWVs so far.

The exterior of this system has only three subtle clues indicating it is equipped with the STS, specifically a stationary forward and aft mounted camera and special STS antenna mast as seen in Fig. 11. This vehicle has been tested by Omnitech Robotics at Buckley Air National Guard Base in teleoperated control at speeds up to 60 m.p.h. while driving on a closed loop course. Qualitative teleoperated driving tests demonstrated complete vehicle control comparable to a human driving the vehicle from the drivers seat.

B. Off Route Smart Mine Clearance

The Off Route Smart Mine Clearance (ORSMC) effort is part of the Joint Countermine ACTD, and a joint initiative with the PM Mine/Countermine and the UGV/S JPO. In general the ORSMC objective is to develop technologies and concepts to neutralize advanced off-route smart mine systems to clear the way for obstacle breaching and main supply route clearing operations. This initiative produced two teleoperated HMMWVs that were then fitted with acoustic and seismic signature synthesis payloads and thermal and radar signature management techniques. This system is designed to counter smart mines that initiate based on the presence of acoustic, seismic, thermal, or radar signatures of high value tracked vehicles like main battle tanks. Active deception techniques are being used to simulate the acoustic and seismic signatures of tactical vehicles. Thermal IR and millimeter wave radar signature management reduces the signatures of the platform to avoid detection by the sublet munition terminal sensors. A thermal target decoy is projected in front of the vehicle to trigger side attack IR sensors and divert them from impacting the main vehicle, thereby achieving mine clearance.



Fig. 10: The STS mounts in the HMMWV behind the drivers seat in the passengers foot well.

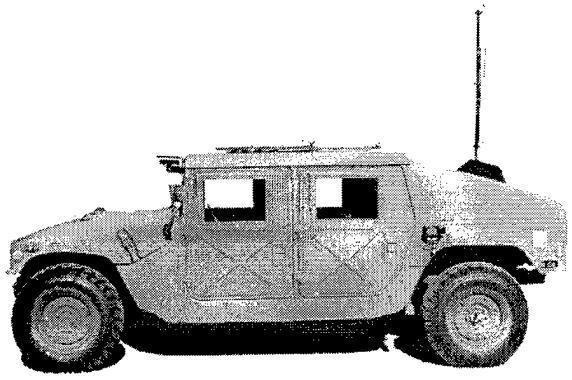


Fig. 11: The IVMMD uses fixed cameras in the front and rear of the HMMWV and a special antenna mast.

The STS installation for this HMMWV, (Model M998, Truck, Utility: Cargo/Troop Carrier, 1-1/4 Ton, 4x4), is nearly identical to the IVMMD installation, with the exception of the mounting of the front and rear cameras and antennas. Fig. 12 shows the ORSMC system in it's final configuration with signature management and active deception techniques in place. This system was successfully demonstrated at a battlelab demonstration at Ft. Benning, GA in the summer of 1996.

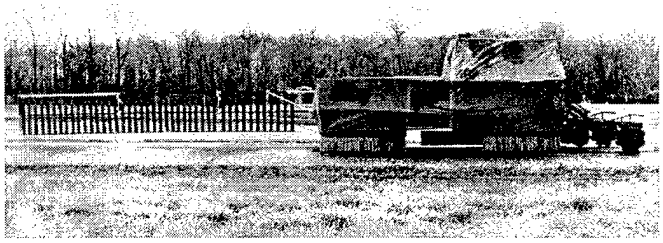


Fig. 12: The ORSMC System uses a teleoperated HMMWV with signature management and active deception techniques

C. Joint Amphibious Mine Countermeasures

The Joint Amphibious Mine Countermeasures (JAMC) program is focused on clearing mines from the shallow water mark up to a cleared landing zone for LCAC landing craft. The vehicle used for this application is the D7G dozer fitted with a mine rake, magnetic signature duplicator, explosive net array, pathfinder clear lane marking system, and a towed chain array.

Two systems were developed in 1994 and 1995 to support a Milestone 0 decision and Advanced Technology Demonstration (ATD) in November of 1995. Subsequently, two additional systems are being developed, one operational in November 1996 and one in January 1997. These second generation systems feature significant upgrades of the STS system as well as the countermine payloads and integration resulting from evaluation of the first generation systems. Notable upgrades include reduction of the STS components size (OCU), addition of a simple hand held remote control only capability to allow driving the vehicles off the LCAC, and addition of an integrated GPS based navigation and mapping system to autonomously control the vehicle trajectory, and map the area cleared. Fig. 13 shows a photograph of the JAMC dozer as configure for the ATD in November of 1995.

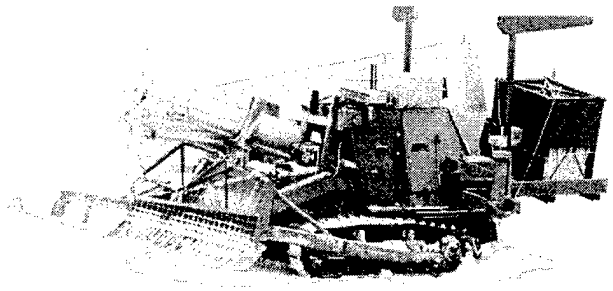


Fig. 13: The JAMC system uses a Caterpillar D7G dozer and numerous countermine payloads

JAMC is being developed by the U.S.M.C. MARCORSYSCOM (AWT) with support of Wright Laboratories, Construction Automation Group (WL/FIVC) at Tyndall AFB and support of the UGV/S JPO.

D. Robotic Countermine Vehicle

The Robotic Countermine Vehicle (ROCV) is an experimental concept vehicle consisting of a turret-less M1 main battle tank (MBT) equipped with a track width mine plow, dual Mine Clearing Line Charges (MICLIC), and a Pathfinder clear lane marking system. The first operational ROCV was demonstrated in 1994, and two additional units with upgraded capability including semi-autonomous driving capability are being developed currently.

The mission for this experimental vehicle is "in-stride breach" where ROCV will travel in a manned mode with maneuver forces until a mine field is encountered. Then ROCV personnel will be evacuated from the ROCV to a supporting Armored Personnel Carrier (APC) or MBT, and teleoperation will commence allowing unmanned mine field breaching and clear lane marking using the ROCV while the accompanying MBTs return cover fire if necessary. This promises to reduce engineering soldiers' casualties by giving them a means for in-stride breach while maintaining the protection of armored vehicles. By contrast, the current alternative is to have soldiers dismount and place and detonate explosive charges on the individual mines to achieve mine field clearance, or to wait for engineering vehicles to arrive to clear the mines, potentially while under hostile fire. The ROCV concept promises to speed the deployment of maneuver forces by reducing or eliminating the need to stop and wait for engineering vehicles to arrive to breach the mine field, thereby improving mission performance and reducing casualties. Fig. 14 shows the first ROCV as configured for testing at Ft. Knox, KY in July 1995. ROCV is being developed for the US Army Engineer School, Director of Combat Development, with support of the UGV/S JPO.

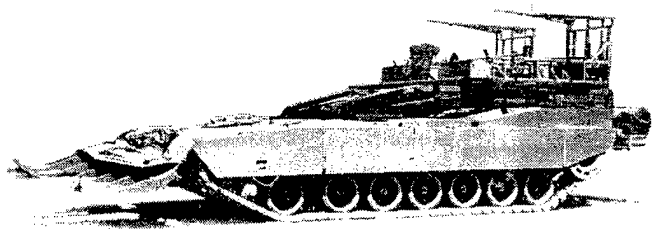


Fig 14. The ROCV uses a turret-less M1 MBT equipped with dual MICLICs, a track width mine plow, and a clear lane marking system

VII. Summary and Conclusion

The Standardized Teleoperation System has demonstrated the ability to remote control, teleoperate and autonomously control a variety of different vehicles for numerous missions. Over 30 systems have been developed so far. It has been successfully operating seven Panther vehicles in different locations in Bosnia for 6 months straight with minimal problems or maintenance. The versatility, portability, and reliability of the STS make it a valuable asset for any mine clearing, proofing, detecting or similar application.

Multi Sensor Vehicular Mine Detection Testbed for Humanitarian Demining

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Abstract - This paper presents research results on a tele-operated multi-sensor vehicular mine detection testbed (VMDT) which was successfully demonstrated by Special Operations Forces at Fort A. P. Hill in November 1995 in support of humanitarian demining. The VMDT uses a combination of several sensors to detect buried anti-tank and anti-personnel land mines. The sensor system included a metal detector array, a thermal neutron analysis (TNA) sensor, and commercial cameras to provide images in the visual, infrared, and ultraviolet bands. The 2-meter metal detector array was shown to be very sensitive to metal, both mines and metal clutter on the test range and it performed well as a primary buried mine sensor. The TNA, as a secondary sensor, detected all anti-tank mines and half pound and larger anti-personnel mines.

I. INTRODUCTION

The Government Operational Capability Demonstration Test (OCDT) was a Congressionally directed program to demonstrate the present state of technologies applicable to humanitarian demining scenarios. Science Applications International Corporation (SAIC) was selected to provide a multi-sensor vehicular mine detection testbed (VMDT) for the OCDT. Most mine detection systems do not in fact detect mines, but rather anomalies such as dielectric differences in soil for radar, induced magnetic fields in the case of pulse induction detectors, or thermal differences in the infra-red. The unique feature of the VMDT was the potential ability of the system to be more than an anomaly detector. The VMDT concept is to use a combination of independent sensors to indicate not just magnetic and thermal anomalies, but also the presence of explosives. Targets can then be classified as mines or clutter. This ability to reduce the false alarms associated with clutter will be an invaluable part of future mine detection and clearance because of the time saved in reducing excavation.

II. VMDT SYSTEM DESCRIPTION

The VMDT consisted of a single tele-operated platform which employed commercial off-the-shelf subsystems configured for two environments, on-route and off-road. The vehicle platform was a Melroe Bobcat modified commercially for tele-operation. The sensor system included a metal detector array manufactured by Schiebel of Austria, a thermal neutron analysis (TNA) sensor developed by SAIC, and commercial cameras were used to provide images in the visual, infrared, and ultraviolet bands. All the sensors, either those employed or earlier models or prototypes, had been proven in mine detection field demonstrations. The visible, UV and IR sensors were forward-looking and were to be used to spot surface-laid or shallow-buried mines. The metal detector was the primary mine detector and the TNA sensor was used for confirmation. The metal detector was set with a discrimination threshold consistent with the desired high probability of detection for minimum metal mines and scanned the path in front of the robotic vehicle. Suspicious spots that triggered the metal detector were interrogated by the TNA sensor.

In the on-route configuration, the sensors were mounted to allow for the maximum area coverage in the minimum amount of time. Figure 1 shows the VMDT on-route configuration at Ft. A. P. Hill during field testing. The Schiebel flexible 2 meter metal detector was mounted on a wear sheet that was dragged along the ground. In combined mode operation, when the metal detector alarmed, the operator stopped the vehicle. The TNA sensor is then positioned over the detection point by advancing the vehicle and positioning the sensor over the suspected mine. The TNA image was analyzed to determine the size and position of the mine. A ground marking device was provided but not demonstrated in the field tests.



Figure 1: Vehicle Mounted Detection Testbed

In the off-road configuration the sensor structure was exchanged for a robotic manipulator arm. This manipulator was a modified Bobcat standard backhoe. The TNA sensor and a 4x4 Schiebel metal detector were mounted on the end of this robotic manipulator. The off-road configuration system was not demonstrated due to time constraints during the tests.

A. Schiebel Metal Detector Array

The primary sensor on the VMDT was a Schiebel metal detector called the vehicular array mine detection system (VAMIDS). The flexible 2 meter VAMIDS was designed to operate from a vehicular platform and detect metallic objects, including land mines with a very low metallic content. The detector consisted of a modular electronics unit housed in a standard military 19" enclosure and individual segments, each with a width of one meter. Inside each 1 meter segment is an array of eight detector heads based on the US Army standard AN-19/PSS-12. The normally audible tone in the presence of metallic targets is converted to a visual display of intensity.

Although the system is designed to be used along roads, it was also shown effective in off-road application. In the field tests it was used as a stand alone sensor and as primary sensor with the TNA as a confirmatory sensor.

B. Thermal Neutron Analysis Sensor

The vehicular mounted mine detection testbed incorporated a thermal neutron analysis (TNA) sensor as a confirmatory sensor to detect the presence of explosives in buried objects that trigger the Schiebel metal detector. The TNA sensor incorporated gamma neutron analysis in a compact sensor with a low intensity isotopic neutron source. These sensors detect ingredients specific to high explosives in the mine. The configuration of the nuclear sensor assembly was compact with a 20 microgram isotopic ^{252}Cf source, eight NaI(Tl) gamma-ray detectors and a single thermal neutron detector contained in a single metal housing. The sensor weight was about 350 lb. and can be used in either the on-route or off-road configuration.

In practice the operator positioned the TNA sensor over the suspicious spot on the ground and activate the sensor. The TNA signals were processed by the on-board signal processing system which formed a TNA image of a buried mine (or ground). The image used a thermal scale to represent the intensity of the mine signal. The image was sent to the VMDT operator console for display.

C. Other Subsystems

The visible, UV and IR cameras were incorporated into a single, camera/optics module which mounted to a pan/tilt mechanism on the tele-robotic vehicle. These cameras were used for initial target identification. Any anomalies detected visually by the operator were interrogated with both the metal detector and the TNA. Other components include the navigation system which is comprised of a wheel encoder, a differential GPS, and a digital compass. The encoder is intended to provide short range accuracy on the order of one inch. It allows one to display images of the metal detector signals and to control the motion of the vehicle in positioning the TNA over a detected target. The differential GPS is intended to provide long range accuracy on the order of one meter or less. It allows one to display a symbol of the vehicle in a navigation window and to record the position of detected targets.

III. Testing Procedure

The Government Operational Capabilities Demonstration Test (OCDT) for humanitarian demining was conducted from September through November 1995. The various mine lanes and sites included the following surfaces: concrete (with and without steel rebar), asphalt, sealed and unsealed gravel, an open grassy field, a plowed farm field, a patterned mine lane in an open area, a small urban area and an unimproved dirt road.

The VMDT was operated and evaluated by Special Operations Forces demining personnel. The test criteria for the operators were:

- To remotely find buried land mines with infra-red and ultra-violet cameras

- To remotely find buried land mines with a metal detector array

- To operate as a combined system to remotely verify if a video or metal detection is an explosive device without digging by using the TNA

To demonstrate these criteria, the operator conducted the following mission sequence. First, the operators determined what search pattern to run based on terrain. Second, the visual, IR and UV video equipment is used via tele-operation to spot surface anomalies. These are noted and interrogated with the metal detector and the TNA. As the VMDT moves forward the operator scans the ground with the metal detector and searches for metallic anomalies. Finally, all metal detections and visual anomalies are interrogated with the TNA sensor to determine if a target is a mine or clutter. Positive targets are then marked for excavation and avoided.

IV Test Results

A. Schiebel VAMIDS Array

The Schiebel 2-meter VAMIDS array was tested on various surfaces including paved roads, unimproved road, a grassy field

and patterned mine area, along with various calibration lanes. The majority of the testing were done using the array in a stand-alone mode. The VAMIDS array proved very sensitive as it detected small pieces of metal and fragments that cluttered the range.

1) Field Calibration Lane

A field calibration lane had been setup between the Farm and the Field Grassy areas. This lane contained a total of 10 mines. The position and type of the mines was known, and the purpose of the lane was to allow the operators to experiment with the response signals before tackling the blind areas.

Fig. 2 shows the response taken with the VAMIDS Manager software on the field calibration lane. The scan was taken at a vehicle speed of about 3.2 km/hr (2 mph). The large metal anti-tank mines are easily and unmistakably seen. This data was acquired with no detonators in the M14 anti-personnel mine. In this scan, the VS2.2 did not have a detonator and was not seen. The VAMIDS did however see the TS50 which also did not have a detonator, showing its high sensitivity. It should be noted that during calibration and trial scans on this calibration lane, much of the metal clutter was detected and removed. The clutter seen next to the M15 and the PMD6 remained. These data were the clearest recorded showing the effectiveness of the VAMIDS in detecting the range of mines of interest to the humanitarian demining program.

2) Grassy Field

The first set of data was collected by Schiebel using the VAMIDS windows software. Fig. 3 shows the recorded VAMIDS response data from the runs on the grassy area. As shown in the figure, the large metal anti-tank mines, M15 and TM46, are easily detected. The figure shows a total of 9 mines detected. The signal response for the anti-personnel mines, both VS50 and PMD6, is very similar to much of the metallic clutter.

B. TNA SENSOR TESTING

To expedite individual sensor testing, the TNA sensor was initially tested on various test areas independent of the metal detector area because of the large quantity of metal clutter on the range.

During the test period, the TNA sensor experienced calibration drifts and had to be frequently re-calibrated. These drifts often caused distortions in the TNA mine image presented to the operator. However, the majority of the TNA data was saved to files which allowed post test processing. Much of the data came from the calibrated reprocessed data. During the actual test period, the TNA sensor demonstrated that it was able to image buried anti-tank and large anti-personnel mines in real time. In most cases the TNA sensor was allowed a time budget of 5 minutes to form an image. During tests on the paved road, tests were conducted to establish a minimum detection time, which was less than 1 minute for anti tank mines. These results are discussed below.

1) TNA Images of Mines

The TNA data was recorded as a set of eight detector responses from which the TNA image was produced. Based on observations in the field, the individual detector response was added to the TNA image screen for the post processed data. In addition, two features indicative of the presence of a mine were added, namely the average signal in all detectors and the average signal in the three detectors with the highest counts. Figs. 4-7 show the TNA images of buried mines of increasing mass. Fig. 7 is the M15 which is the largest of the mines. The real time response is shown in the bar graphs one through eight. Note that in this image detectors 3, 4 and 5 are off the display

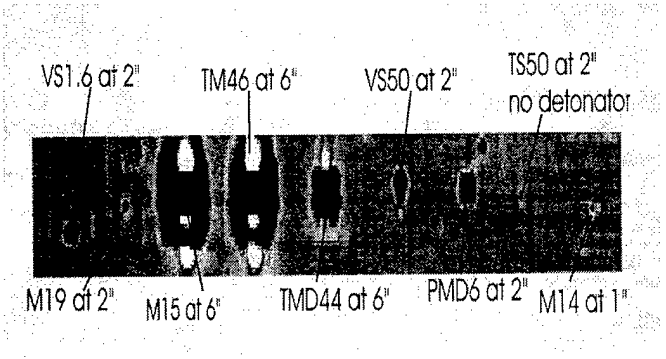


Figure 2: Schiebel 2 meter metal detector scan of field calibration lane

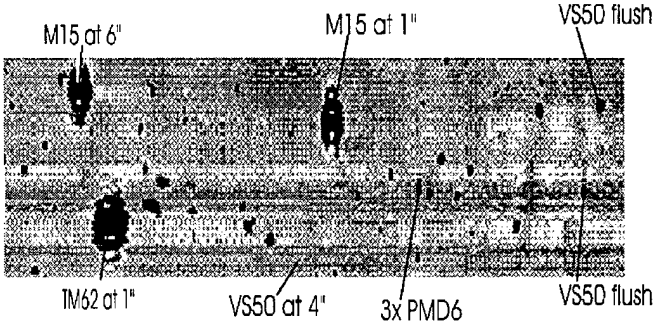


Figure 3: Schiebel 2 meter metal detector scan of grassy field (composite of 4 scans)

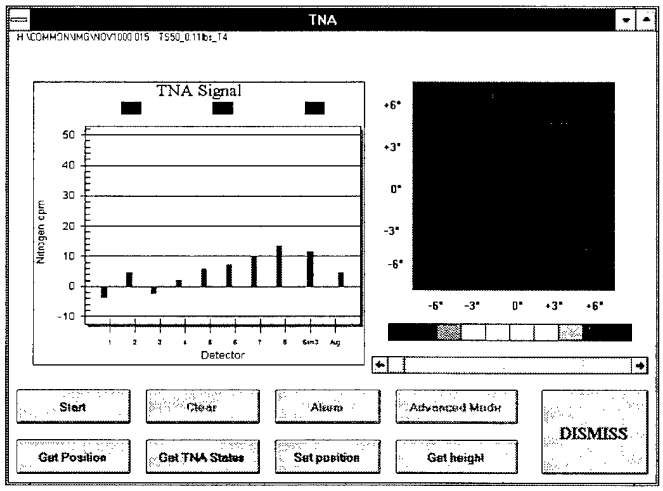


Figure 4: TNA image of TS 50 mine

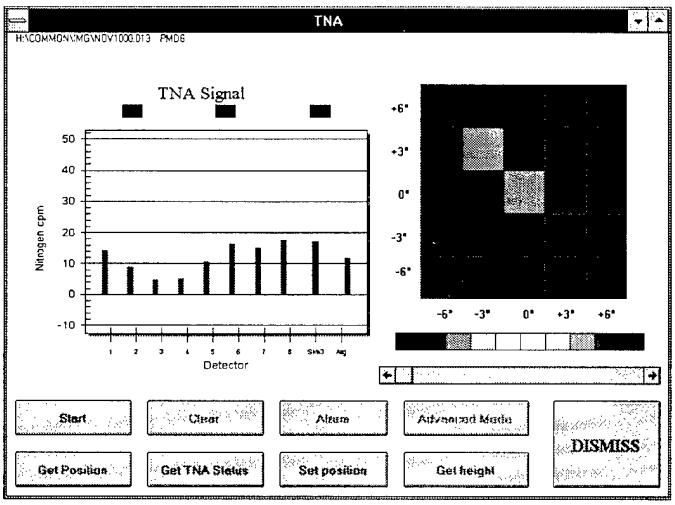


Figure 6: TNA image of PMD6 mine

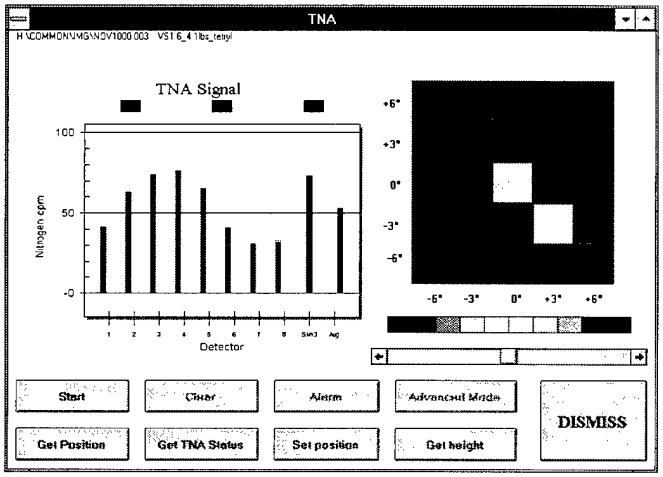


Figure 5: TNA image of VS1.6 mine

scale. The ninth bar graph is the average of the highest three detectors which are also off scale. The tenth bar graph is the average of all detectors. The image on the right is a spatial representation of the mine position under the TNA sensor. The top of the image is the front of the TNA sensor.

2) Field Calibration Lane

The response of the TNA sensor was demonstrated on the Field Calibration. Each mine, except the last M14 mine was measured for 5 minutes or less). The results of these tests summarized in Table 1. The TNA easily detected all the anti-tank mines - both metallic and minimum metal mines. The PMD6 was easily seen although it has only approximately 200 grams of TNT and consequently has a lower TNA signal than the anti-tank mines. Only one of the smallest anti-personnel mines, the TS50 was detected; the VS50 was not. These small anti-personnel mines which have around 45 gm of explosive or less were nominally buried at 2".

3) Patterned Mine Lane Calibration Track

The TNA sensor was tested on the Patterned Mine area Calibration Track following the VAMIDS tests on the patterned mine lane. During these tests the TNA first measured a buried mine and then measured the soil adjacent to the mine to contrast the TNA images. Table 1 summarizes the results for these tests. Although not all the mines in this calibration lane were measured, it was clear that TNA easily saw the large and small anti-tank mines. The TNA also detected the larger anti-personnel mine (PMD6). In these tests the TNA did not distinguish the difference between soil and the small anti-personnel mines (M14, TS50).

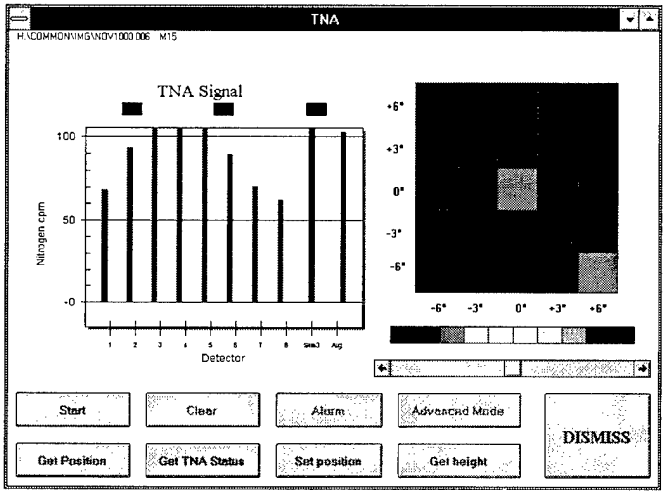


Figure 7: TNA image of M15 mine in soil

TABLE 1: VMDT MINE DETECTION RESULTS

Mine	Mine Type	Explosive/ Quantity	VAMIDS	TNA
M15	Anti-Tank Mines -Metal	RDX/15.4 lb.	Detectable	Detectable
TMD44	Anti-Tank Mines -Metal	TNT Dynamite	Detectable	Detectable
TM62	Anti-Tank Mines -Metal	HE/15.4 lb.	Detectable	Detectable
M19	Anti-Tank Mines -Plastic	Comp B/20 lb.	Detectable*	Detectable
VS2.2	Anti-Tank Mines -Plastic	Comp B/4.7 lb.	(data not recorded)*	Detectable
VS1.6	Anti-Tank Mines -Plastic	HE/4.1 lb.	Detectable*	Detectable
PMD6	Anti Personnel Mines -	TNT/0.44 lb.	Detectable	Detectable
M14	Anti Personnel mines	Tetryl/0.06 lb.	Detectable*	Below demonstrated
TS50	Anti Personnel mines	T4/0.11 lb.	Detectable*	marginal (detected once)

*when detonators present

4) VMDT Operational Mode Testing

VMDT was tested in an operational mode in which the VAMIDS and TNA worked together with the metal array triggering and the TNA immediately interrogating detected targets. In this way it was demonstrated that the TNA performed well as a confirmatory detector - clearing false alarms and confirming the presence of buried mines.

The unimproved road consisted of a relatively flat section and an adjacent vehicle tire rutted area. During the tests, the VMDT advanced until the VAMIDS had an alarm. The VMDT would then stop and move back and forth to maximize the VAMIDS response to determine the suspected mine position. The ground positions of the VAMIDS triggers were then marked with spray paint. The VMDT vehicle was then moved forward under tele-robotic control, and the TNA sensor positioned over and lowered onto the suspect location. Those VAMIDS alarms that were declared to be mines by the TNA operator were marked with a flag.

On the rutted part of the unimproved road, the VAMIDS sensor alarmed on the two metal anti-tank mines and a coffee can buried as clutter. The TNA sensor confirmed the two metal mines and indicated the can did not contain explosives.

These tests on the unimproved road were the only true operational tests of the combined VAMIDS/TNA sensor system. They were successful in demonstrating that the two sensors could be used to identify suspect locations and confirm the presence of mines. The VAMIDS is a very sensitive, rapid detector of metal but metal is not specific to mines. The TNA signals are specific to mines with an interrogation time much longer than for the metal detector. Thus the TNA is well suited as a confirmatory sensor.

5) Special Note on Limitations of TNA

The net nitrogen signal is to the first order proportional to the nitrogen mass in a mine, but is modified by burial depth, stand off and other effects. The nitrogen mass in the mines used in the various test areas is shown in Table 2.

Practical field experience indicates that at least a half pound block of TNT (such as the PMN or PMD6 AP mines) is required to activate the detector reliably for real time operations. Potentially the system will detect the smaller mines such as the TS50 in post processed applications where a field is swept, the data stored, then analyzed later.

TABLE 2

Mine	Mine Type	Explosive	Qty(gms)	%N	N-gms
M19	Anti-Tank Mines -Plastic	CompB	9091	31%	2773
TMD44	Anti-Tank Mines -Metal	dynamite	9545	18%	1718
M15	Anti-Tank Mines -Metal	RDX	7000	38%	2660
TM62	Anti-Tank Mines -Metal	HE(TNT)	7000	18%	1260
VS2.2	Anti-Tank Mines -Plastic	CompB	2136	31%	652
VS1.6	Anti-Tank Mines -Plastic	HE(CompB)	1864	31%	568
PMD6	Anti Personnel Mines -large/metal	TNT	200	18%	36
M14	Anti Personnel mines small minimum metal	Tetryl	29	24%	7
TS50	Anti Personnel mines small minimum metal	T4	50	38%	19
VS50	Anti Personnel mines small minimum metal	RDX	43	38%	16

C. UV/IR CAMERAS

The UV and IR cameras were demonstrated to be functional during the early field integration period. The testing of these sensors was given a lower priority than the testing of the VAMIDS and TNA sensor. No tests were carried out in the optimal conditions for use of these cameras.

IV. CONCLUSIONS

The tele-operated vehicle generally performed well and satisfied the demonstration criteria in that all vehicle mine detection operations were conducted remotely. The Schiebel 2 meter VAMIDS array was shown to be very sensitive to metal, both to mines and to metal clutter on the test range and easily met the demonstration criteria. Field observation of the VAMIDS performance on the paved road showed it could detect the buried metal anti tank mines even with rebar in the cement. Overall it performed well as a primary in the combination of sensors. The video subsystems as detectors were not adequately tested due to the poor environmental conditions present during the demonstrations. No assessment can be made about the ability of the visual, IR and UV sensors to satisfy the demonstration criteria.

The TNA sensor was successfully able to confirm or deny the presence of explosives in all anti-tank and some anti-personnel land mines in real time during the demonstration. In addition, the field data was stored and analyzed in the post-test period. This analysis showed the TNA sensors were able to detect all anti-tank mines and the anti-personnel mines of a half pound or more. For the smallest anti-personnel mines the TNA had marginal performance. The TNA was shown to be insensitive to road and field surfaces, and clutter objects. Overall, the TNA demonstrated the ability to function as a confirmatory sensor and met the demonstration criteria for large mines.

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Tele-operated Ordnance Disposal System for Humanitarian Demining

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Abstract - This paper presents research results on a system used to excavate anti-personnel and anti-tank land mines using a tele-operated off the shelf skid steer loader. The Tele-operated Ordnance Disposal System (TODS) was successfully demonstrated by Special Operations Forces at Fort A. P. Hill in November 1995 and in August 1996 in support of humanitarian demining. The TODS consists of a tele-operated arm which has a bucket, a gripping claw, and an air knife and was successfully used to excavate land mines. An off the shelf metal detector was used to pinpoint unmarked targets. In a second operational mode, an off the shelf bushhog was attached and used to remotely clear dense vegetation for deminers. The TODS successfully demonstrated the capability to clear vegetation and excavate mines within specific test criteria. The TODS was developed by OAO Corporation, in Greenbelt, MD, as part of the Congressionally directed Humanitarian Demining Technology Program.

I. INTRODUCTION

A. Background

The United Nations estimates that there are approximately 110 million land mines laid in 62 countries in combat zones, and civilian commercial and agricultural areas. At the current rate of clearance, time estimates range from hundreds to thousands of years to complete the cleanup. This rate is clearly unacceptable for humanitarian and economic reasons. In the humanitarian sense, the majority of the casualties are noncombatants and frequently children. Financially, agriculture based economies cannot withstand the denial of vast tracts of farmland because of the mine threat for hundreds of years. The application of technology not only has the potential to increase mine clearance to an acceptable rate, but will also provide safer methods. Deaths and injuries due to mines occur not only in the general population, but also to personnel specifically trained to conduct humanitarian demining operations. Specific instances include Kuwait in which, 84 demining experts were killed or maimed during the cleanup, and of a local demining team of 49 in northern Somalia, 17 were killed or injured in accidents over the past 3 years[1]. A solution is needed to solve the mine clearance problem by increasing the rate of clearance with the constraint that casualties are unacceptable in humanitarian demining.

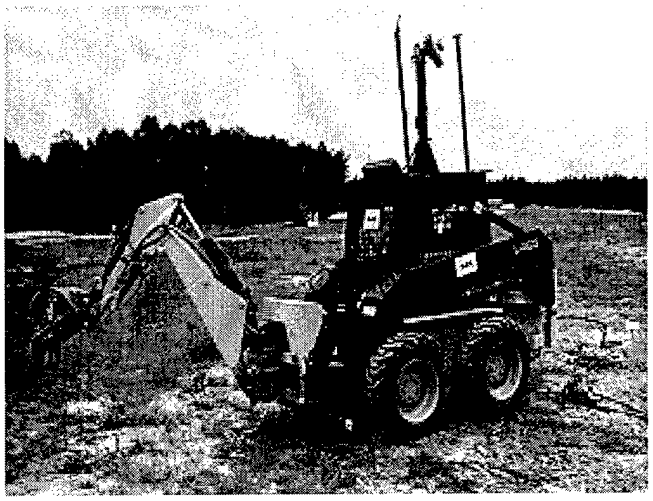


Figure 1: Manipulating arm with bucket attachment and metal detector

B. Demonstrated Results

A solution to the problem is the Tele-operated Ordnance Disposal System (TODS). The TODS is an off-the-shelf skid steer loader modified for tele-operation with mechanical mine clearance capability (see Fig. 1). In 1995, it was selected to demonstrate mine clearance capability in the Congressional directed Operational Capability Demonstration Test (OCDT) at Fort A. P. Hill. The following paper describes the system, the test requirements, and discusses the results of TODS demonstration.

The TODS is composed of three main subsystems. First is the chassis which is a diesel powered commercial skid steer modified for full tele-operation capability. This includes two remote cameras, a portable base controller, and differential global positioning system (GPS) navigation system. All other subsystems are attached to and controlled from the chassis. The second is the manipulator arm which is a commercial backhoe that can be used with either an excavation bucket or a mechanical gripper. They are interchangeable and can be swapped in minutes. The bucket attachment is used to excavate mines or dig trenches. A commercial metal detector is used in conjunction with the bucket when needed to pinpoint targets that are either

bucket when needed to pinpoint targets that are either approximately or electronically marked. In place of the bucket, the gripper attachment can pick up mines or place demolition charges near mines too sensitive for human approach. The arm also has an articulating air knife which is used to clear soil with compressed air from targets to aid in identification. The third subsystem is a commercial bushhog which is installed for specific missions in place of the manipulator arm. Frequently in humanitarian demining, the war ended years before and footpaths and farms are impassable by deminers because the abandoned mined areas are overgrown. Deminers must cut grass by hand and search for and clear mines on an inch by inch basis. With an added commercial bush-hog, the TODS can be used from a standoff to safely cut heavy brush suspected of being infested with mines so that detection and clearance equipment can follow.

The following sections describe the test criteria, procedures used to evaluate the described subsystems and the demonstration results.

II. Test Demonstration Criteria

A. Criteria for Test

The most important criteria for mine clearance in humanitarian demining is safety. Since the TODS is tele-operated and the human operators are located outside the danger radius of the effects of an accidental mine detonation, safety is assured by design.

On a system level, operationally the TODS must be easy to use, able to navigate to a marked minefield, identify and excavate targets, and prepare mines for disposal. The test criteria specify that the task must be accomplished in a time equal to or better than current methods, and without detonating the mines.

On a component level, the test criteria are identified into the following categories: Chassis, vegetation cutter, and the manipulator arm. For the chassis, test criteria specified that the tele-operation system must be able to control the vehicle and all functions easily and with little training. The navigation system must at a minimum be able to navigate to within 20 meters of an electronically marked minefield, and at best within 2 meters of an electronically marked mine. Within this range the visual cameras are to be used to locate the marked targets for excavation.

The criteria for the vegetation cutter was qualitative and stated that the TODS operator was to remove light and heavy vegetation to the lowest level the bushhog could reach with no operator line of sight. All operations were to be performed via tele-operation.



Figure 2: Air knife exposing mine

For the manipulator arm, each attached component had specific test criteria to meet. The air knife criteria stated that it must be capable of removing soil from the top of anti-tank and anti-personnel mines without activating the fuzes. All targets were to be precisely located, identified, and classified before excavation so that the bucket could be placed behind and dug underneath mines to prevent accidental activation (see Fig. 2). The bucket criteria stated that it had to be capable of excavating all mines from the smallest plastic anti-personnel mine near the surface to the largest metal anti-tank mines buried up to twelve inches. Excavation should be completed without activating the mine fuzes. The criteria for the gripper attachment stated that it was to be able to pick up, transport, and place all mines without activating the fuzes or crushing the small mines. With these test criteria in mind, Special Operations demining personnel developed the following scenario to demonstrate the capabilities of the TODS.

B. Operational Scenario

The operator of the TODS was given a simulated demining mission to conduct which included the following steps. First, the operator was to navigate using real-time GPS data from a base station to the coordinates of previously identified suspected minefield using the TODS teleoperation capability. The operator then used the vegetation cutter to clear brush from the area. Other mine detection was used to detect and mark, physically and electronically, individual targets in the minefield which was not part of this demonstration. With the manipulator arm installed on the TODS, the operator navigates it to within 2 meters of the electronically marked mines, visually locates ground marks or uses metal detector to pinpoint a target location. The operator then uses the air knife to uncover the target, clearing all soil from the top. The

operator identifies the mine, uses the bucket to excavate it. The mine is then stored and the operator digs a disposal pit. The bucket is replaced with the gripper arm so that the operator can pickup, transport, and place the mine with others in the disposal pit.

The test criteria specify that this operation was to be conducted in a time equal to or less than the current method of manual mine clearance, and without detonating the mines. This procedure was repeatedly conducted and timed so that a reliable assessment could be made as to the average time these operations could be completed. Also, most of the mines had smoke fuzes or other mechanisms to indicate if a mine fuze was activated during clearance. The test operators and evaluators were a combination of Special Operations demining personnel as well as contractor and Army program personnel. The following section details the numbers and types of mines used.

C. Threat Land Mines Used

The system was tested against 87 anti-tank (AT) mines representing three weight classes, two shapes and two material types as shown in Table 1. 87% of the mines are "old," meaning that they have been buried for 4 months or more. The remaining 13% are "new," meaning that they have been in the ground for 1 week or less. The significance of using old mines is that sufficient time will have passed to allow for rainfall and settling of the fine soil around the mine. The result is that the soil is tightly packed around the mine case and they are more difficult to excavate than freshly buried mines. These long buried mines represent the majority of the threat faced in Humanitarian Demining in which the conflicts are long over. 71% are shallow buried, which is defined as 1 inch or less. The remaining 28% are deep buried, which is 6" or more. This is an approximate mix of the depths that are encountered in real demining situations.

The mines were all excavated in a random order, so that the depth and type of mine were unknown to the operator. His only indicator was a flag near the location of a target.

TABLE 1
ANTI-TANK MINE TEST POPULATION

AT Mine Population	QTY	Breakout by depth		Breakout by age in ground		Breakout by Type	
Size		1"	6"	Old	New	Plastic	Metal
Large (16 - 25 lb.)							
M19 (square)	23	13	10	16	7	23	
M15 (round)	34	25	9	30	4		34
Medium (8 - 15 lb.)							
TM-60 (round)	10	10		10		10	
M-6 (round)	20	14	6	20			20
Totals	**87**	**62**	**25**	**76**	**11**	**33**	**54**

TODS was tested against 64 shallow buried anti-personnel (AP) mines as shown in Table 2. 70% of the AP mines are old and 30% are new.

TABLE 2
ANTI-PERSONNEL MINE TEST POPULATION

AP Mine Population	QTY	Breakout by Age in Ground		Breakout by Type		
Size		Old	New	Plastic	Metal	Wood
Large						
PMN, 5"	26	20	6	26		
Medium						
PMD-6, box 7.5"l, 3.5"w, 2.5"h	15	15				15
Mk-2, 3"	10		10	10		
OZM, bounding, 2 lb.	10	10			10	
Small						
M-14, 2.25"	3		3	3		
Totals	**64**	**45**	**19**	**39**	**10**	**15**

III. Discussion of Test Results

The following paragraphs discuss the test results in the areas of navigation, vegetation clearance and mine excavation. In general, the TODS was described as easy to operate and required a few minutes of instruction to get an operator started. After a few practice rounds, all operators were able to efficiently excavate mines. The Special Forces operator involved in the test program, with no previous training with this backhoe system, consistently out-performed in excavation the OAO engineers who had logged multiple hours of training prior to arrival at Fort A. P. Hill.

A. Navigation.

The test criteria specified that the GPS navigation system had to be 20 meters accurate at a minimum, and potentially guide the TODS to within two meters of a specified location. The system worked well enough to guide the vehicle in real time to designated minefield boundary markers. The TODS easily satisfied the minimum capability. It proved to be consistent through a series of seven test runs and multiple position verifications tests throughout the demonstration period. The rate of advance using only the GPS was limited only by the maximum forward speed of the vehicle which was approximately 6 mph.

For individually marked targets, the TODS GPS system had a precision of plus or minus 1.1 meters limited by the last significant digit in the operator's video overlay data display. When the TODS was parked over a surveyed GPS marker it took about four minutes for the system to hone in on the exact location rounded to the precision of the system. From this range, all marked targets were easily identified using the visual cameras of the tele-operation system.

B. Vegetation Clearance.

The test criteria for the bushhog are a qualitative statement on the ability of the system to cut light and heavy vegetation without endangering the deminer. This required that the cutting operations be completed via tele-operation with no operator line of sight. Over the course of the test period, the TODS proved to be effective at clearing large areas rapidly, and tight areas with little room for movement all via tele-operation. Also, the operators of the TODS had no trouble with any vegetation from high grass to densely vegetated areas that even contained small trees. An important note for the reader is that the system only clears as far into the minefield as the cutter can reach (about two meters) before the wheels of the chassis enter. Thus clearing procedure requires that an edge strip of a minefield is cut, checked for mines, cleared of mines, and the process is repeated (see Fig. 3). The key point is that the operator operating the TODS remotely and is not exposed to the effects of a sensitized mine or booby trap detonation.



Figure 3: Bushog Attachment

The vegetation clearance operations were conducted in several mission scenarios. None of these clearance scenarios include time required for mine detection which was not part of this program. The first was to clear an area containing high grass, weeds and small trees. This 20 x 30 meter area was successfully cleared with no operator line of sight in about 30 minutes. The second was to clear the side of a hill covered with high grass that was suspected of having anti-personnel mines. This 2 x 8 meter area was more challenging because of the off-road nature of the terrain but was also completed in 30 minutes. The third was to clear a simulated off road area of heavy brush with varying terrain. This 4 x 50 meter area was successfully cleared within 30 minutes so that off-road detection devices could be brought in to search for mines. All of these areas would have taken hours if done with the current method of hand clippers because of the danger of accidentally detonating mines.

The fourth scenario incorporated the ability to clear a pattern around various obstacles simulating an urban area. The backhoe mounted camera was also moved to the reach riser boom to provide a fixed, side-angle view of the cutter. This operation was also easily completed.

The vegetation cutter is a standard commercial item that met qualitative test criteria. Deminers can utilize the tele-operated bushhog attachment as an effective tool to safely clear brush in hazardous conditions.

C. Excavation.

The first part of the criteria for excavation required that the mines be precisely located and identified before they were excavated with the bucket. This way, the bucket could start behind the mine and scoop underneath so that no contact was made with the pressure plate on top. The air knife mechanism

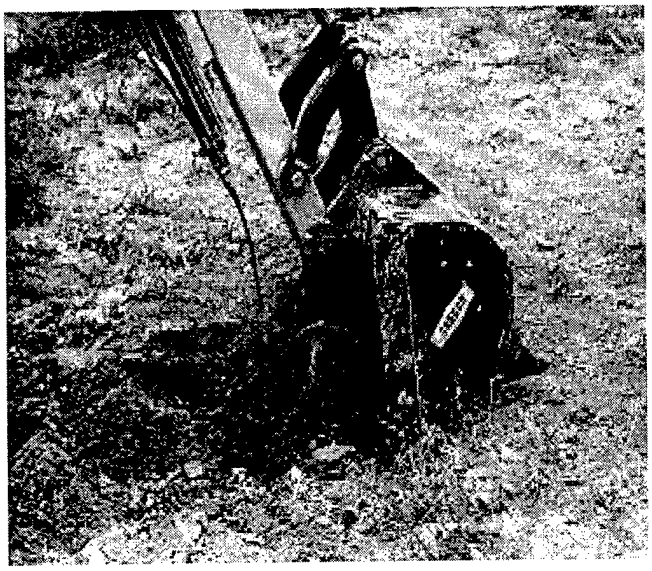


Figure 4: Bucket attachment excavating AT mine

incorporated an automatic X-Y dithering motion which was activated via a remote switch. It proved to be extremely effective in assisting the operator to initially locate and identify the mine without causing detonation. The air knife was most effective in dry soil, and would clear the top soil from shallow buried anti-personnel mines and anti-tank mines in an average of less than 3 minutes and less than 6 minutes respectively. See Table 3. The air knife did well in clay-soil conditions but was not effective in muddy conditions.

The bucket and air knife were used in conjunction for clay or dense soil conditions and deep mines by lightly scratching the soil surface with the bucket and blowing away the soil with the air knife (see Fig. 4). This process would be repeated until the operator visually acquired the mine through the remote video system. The air knife also proved effective after transporting and dumping the mines when they were occasionally re-buried by the soil contained in the bucket. This occasionally occurred during excavation of the anti-personnel mines.

Once located and identified, the mines were excavated with the bucket attached to the backhoe arm. The average time for excavation for the mines are presented in Table 3.

Table 3.
Average Remediation Times (min:sec)

Average Time To:	*AP*	*AT*
Start to Locate	2:23	5:41
Locate to Identify	0:26	0:25
Excavate	3:11	3:08
Total Elapsed Time	6:00	9:14

For this table "locate" is defined to be the first visual acquisition of target. The air knife is being used in this stage. "identify" is defined to be the instant that the operator recognizes the mine type. This is the time period when the soil is being cleared from a suspected target so that the entire top surface can be viewed. "excavate" is the time elapsed until the mine is in the in backhoe bucket. The total elapsed time is the average entire event for each mine with the high/low disregarded and this represents a conglomerate of five different operators over a period of seven days. Transport time was site/scenario specific and was not used in the calculations.

The key result is the time required for excavation. For a total of 151 mines, almost all mines were excavated on average in less than 10 minutes. This rate is comparable, and probably better than the current manual method. The most important note is that this was all completed via teleoperation and even in the event of an accidental mine detonations or booby trapped mines, there would have been no casualties.

A qualitative analysis on the test site indicated that as the operator became more familiar with the TODS, he also became faster. An quantitative analysis was completed on the operator's timed excavations to determine if the observation was supported by recorded data. The results are presented in Table 4. Potentially, these numbers indicate that an experienced demining team would meet or surpass the test criteria.

TABLE 4
LEARNING CURVE - ELAPSED TIME (min:sec)

Oper	*1-5 Av*	*6-10 Av*	*11-20 Av*	*20+ Av*
#1	17:36	18:24	9:18	8:09
#2	15:12	7:24	3:00	4:33
#3	8:12	9:12	7:12	N/A

Though the main charge of all mines is inert, to satisfy the criteria of no mine detonations, some of the mines were equipped with special smoke fuzes, or were configured so that if the mine were set off during excavation, government personnel could verify the event. Detonation data is provided in Table 5.

TABLE 5
RECORDED DETONATIONS OF INSTRUMENTED MINES

Mines:	total excavated	total detonated	Notes
All Anti-tank	87	9	
M-15	34	1	deep buried
M-6	20	0	
TM-60	10	1	shallow buried
M-19	23	7	1 shallow, 6 deep
All Anti-personnel	19	4	
PMN	6	2	
M-14	3	1	
Mk-2	10	1	



Figure 5: Manipulating arm with bucket placing mine in trench for destruction

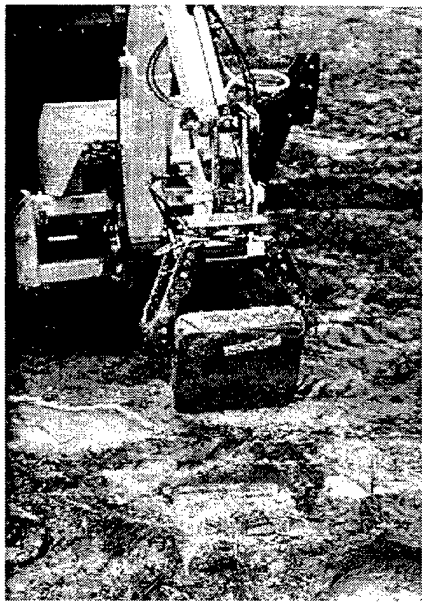


Figure 6: Gripper excavating M19 AT mine

Initially, the TODS was not meeting the criteria of avoiding mine detonations. However, all of the fuze initiation incidents occurred early in the test program. The activation of the anti-tank mine fuzes was a function of operator training and familiarization. As the operators learned of the results of each excavation that caused a detonation and discussed the causes, new excavation techniques were developed that precluded any further fuze activation. The newly developed techniques included using the air knife to not only find and identify each target, but also to completely clear the top of each mine. This procedure insured that the operator could not place the digging bucket in a position where it could accidentally contact the pressure plate of the mine. Also, the excavation process was adjusted by adding the following extra step. The operator would dig a small trench behind the mine so that the bucket could scoop far below the mine to remove it from the soil. This prevented the bucket from spearing the side of the mine or skipping up over the top edge. These techniques prevented further fuze activation, which is an important part of the test criteria. These same techniques were also used to avoid activation of the small mines and were demonstrated successfully in the later stages of anti-personnel mine excavation.

As the mines were excavated they were either transported in the bucket to a common staging area or placed along side the excavated hole. Once a sufficient amount of mines were unearthed, the TODS was used to dig a trench approximately 15 feet long, two feet deep and 18 inches wide. See Fig. 5. The TODS manipulator arm was reconfigured from the bucket attachment to the gripper assembly so that the mines could me precisely placed in the pit. The system was used to pick up the individual mines and stack them in the trench for disposal. The operators were easily able to use the grippers even in muddy conditions to complete the task without activating a single anti-tank or anti-personnel mine fuze.

A final important note about the excavation of the mines concerns two special mines that simulated unexploded ordnance (UXO). The excavation of these two targets was not included in the test criteria but was meant to establish a bound on the capability of the TODS. The two inert full weight M-15 mines were buried 36 and 38 inches respectively from the surface four months before the demonstration. These represented UXO that had penetrated the ground on impact, or very long buried mines that were in an area where soil washed over and built up as seen in Kuwait and Southeast Asia. The operators were easily able to excavate these targets from these depths. This result exceeded the expectations of the capabilities of the TODS.

All of these tests and results led to the conclusions in the following section.

IV. Conclusions

The TODS operators were able to meet the test criteria in the following areas: safety, ease of operation, vegetation clearance, GPS and visual navigation to both minefields and individual mines. Also, criteria for tele-operation and remote control capability, mine manipulation with the gripper, mine identification and preliminary excavation with the air knife without activating the fuzes were also met. The digging bucket was capable of excavating all mines from the smallest plastic anti-personnel mine near the surface to the largest metal anti-

tank mines buried up to twelve inches. Operators also demonstrated the TODS can reach mines buried 38 inches deep. Later stages of testing also demonstrated that experienced TODS operators were capable of excavating all mines without activating the fuzes.

The TODS concept is the application of commercial technology to the problem of land mine remediation. It is a technologically important solution in that it provides fully remote capability for deminers in a situation where casualties are unacceptable.

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Mine Marking and Neutralization Foam

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Jason Regnier, Project Engineer, U.S. Army CECOM NVSED

Abstract—This paper presents research results concerning a system for effectively marking and neutralizing anti-personnel land mines by employing a unique single-use kit containing a rapid-rise-and-cure, rigid-foam material. Because of its simplicity and ease of use, this foam is highly suitable for immediate use in humanitarian demining. The foam and dispensing system were developed by Hughes Aircraft Company, El Segundo, CA, as part of the Congressionally directed Humanitarian Demining Technology Program.

Each kit consists of liquid foam components packed in a twin disposable cartridge together with a mixing nozzle, all sealed in an aluminum foil bag. The foam expands to many times the liquid volume, forming a bright orange-red, easy-to-see mound over a mine. It is applied over exposed mines using a manportable, manual, double-caulking gun dispenser or by simply mixing the components in the foil packaging bag and pouring the contents around the mine. Operationally, the foam impregnates the exposed parts of a mine prior to curing and hardening, rendering the fuse inoperative. The bright color of the hardened material clearly marks the location of the mine. While the hardened foam does not destroy mines, it makes them safer to handle for subsequent destruction. The cured foam distributes loads applied (i.e., foot pressure) over a much larger surface than a mine's pressure trigger area, substantially reducing the likelihood of detonation. It also enables the attaching of a rope to any anti-personnel mine so that the mine can be pulled from the ground at a safe distance. The rope is placed next to the mine, and the chemicals are spread over it and the mine before the foam hardens.

In the 40 field tests conducted by Army Special Operations Forces on ten different mine types, the foam marked, neutralized, and aided in the removal and destruction of anti-personnel land mines. It functioned in cold and warm weather, and under wet and dry conditions. The foam neutralized both pressure-fused and tripwire-fused mines. The foam will not impede the effectiveness of conventional explosive charges in destroying the mine.

The foam consists of a water-blown, two-part 50:50 mix ratio polyurethane foam to which a dye is added. The nonflammable, environmentally benign foam material is dispensed as a liquid and cures to a hard, smooth surface. This foam material was selected because its rise and gel time are fast enough for field use even at low temperatures, but do not cause the foam to lift the mine as it expands, possibly triggering anti-tamper devices. At room temperature, the foam rises and is tack free within 5 minutes. At near-freezing temperatures, approximately double this time is required. The foam material components and dispenser were intentionally chosen to be low-cost, commercially available items. Commercial sources for packaging the foam kits are being developed.

I. Background

The planting of land mines and booby traps has become one of the chief ways of providing effective, low-cost barriers against land forces. Analysis of past conflicts shows mines and booby traps cause more casualties in low-intensity conflict theaters than any other factor. Further, the mined and booby trapped area continues to be a dangerous threat to the area's inhabitants long after a conflict has ended. The United Nations estimates that 110 million live land mines remain to be located and neutralized in 64 countries. Many of these cheap, easily portable weapons can be detonated by the pressure of even a child's footstep. About 100,000 mines are found and disarmed each year, but meanwhile millions more are planted. Current figures show that, for every mine neutralized, seven more are being planted [1].

Widely diverse mines are available today. Mines used in Third World countries range from clandestine, homemade devices fabricated from indigenous materials to sophisticated military devices of American, NATO, Eastern Bloc, and Third World origin. These mines use military explosives such as pentaerythrite tetranitrate (PETN), cyclonite (RDX), and C4; commercial explosives such as dynamite, TNT, black power, and nitroglycerin; and homemade explosives such as ammonium nitrate (fertilizer) and fuel oil (ANF), potassium perchlorate and aluminum powder, and sodium chlorate and petroleum jelly.

Triggering devices that detonate the explosives can be divided into two basic types: pull and pressure activated. Military-designed pressure devices such as the M1A1 and M5 (mousetrap) and M1 pull firing devices (and their Eastern Bloc counterparts), utilized for their reliability and resistance to the environment, are fairly common. Clandestine devices made of indigenous materials are, however, also encountered frequently. All of these devices can be silently and quickly deactivated by a rigid, foam-in-place material interfering with the operation of triggering devices (Fig. 1). The hardened foam can prevent the firing pin on an M1 pull firing device from striking the percussion cap or prevent the metallic contacts on a clothespin device from closing (completing the circuit and initiating an explosion).

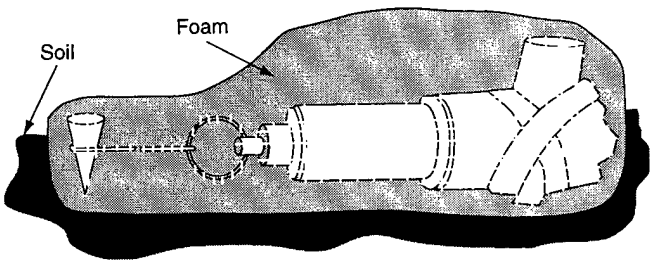


Fig. 1. Mine encapsulated, marked, and disabled by foam. An M1 pull triggering device and tripwire are fully encapsulated in foam that prevent the pin from dislodging and detonating the mine.

II. Introduction

The purpose of this project was to develop a simple, hand-held, portable, single-use system for marking all types of land mines and disabling selected types of anti-personnel land mine triggering devices. This task included fabricating several kits of a selected mine marking and encapsulating material and associated dispensing equipment.

The objective was to develop a rigid polyurethane foam with suitable colorant to mark land mines and disable them where possible. It included development of a way to package the liquid foam components in commercially available cartridges that could be used with a commercially available dispensing system.

The intent was not to render mines harmless, but to render them inoperative and so make the mined area safe to cross without requiring detonation. Specifically, the aim was to freeze tripwire fuses in place and to prevent detonation of some pressure/deflection-triggered mines by increasing the load-bearing area above them. An adult standing on the foamed area would not transmit more than 10 pounds nor more than 30 mils of deflection to a detonation pressure plate.

III. Results And Discussion

A. *Foam Formulation*

The foam formulation chosen consisted of a two-part MDI (polymeric diphenylmethane 4,4 diisocyanate)-cured, water-blown polyurethane foam mixed with a bright fluorescent colorant. The final formulation (Table I) consisted of a modified commercial foam made by Urethane Technologies, Inc. (Polymer Development Laboratories Division, Orange, CA), PDL No. 328-4 FAST, combined with a Magruder Color Company (Radiant Color Division, Richmond, CA) orange-red pigment, No. R6-OR9014.

The foam was dispensed using a Techcon Systems (Carson, CA) No. TS 529S double-cylinder manual caulking-type gun. Polycarbonate splash shields (6 x 8 x 1/8 in.) attached to the front and rear of the gun (Fig. 2) also provided a convenient method for resting the gun in an upright position. (These shields prevent foam chemicals from contacting the operator. They do not provide sufficient protection, however, to prevent injury from concussion or debris should a mine detonate.) The foam was packaged in a pair of Techcon System II No. SII300S polyethylene 300 cc cartridges and dispensed through a Techcon No. TSD 160-830 static mixing head nozzle that swirls and mixes the two urethane chemical components as they are extruded.

Six other foam materials were evaluated before the material described above was selected (Table II).

Tests with simulated mines showed that the rise and set times of the PDL 707 foams were too rapid. When applied, they tended to lift mines out of loose soil, possibly causing an anti-disturbance device attached to an actual mine to trigger. Also, the cured surface of this family of foams was rough and uneven.

TABLE I
Mine Marking Foam Formulation—A Combination of Two Commercially Available Materials

Material designation	Isocyanate Part A (pbw)[a]	Polyol Part B (pbw)
PDL 328-4 FAST	100	73
R6-OR9014	—	13

[a]pbw = parts by weight

Note: This formulation provides for a 1:1 by volume mixture due to differing densities of the Part A and Part B materials.

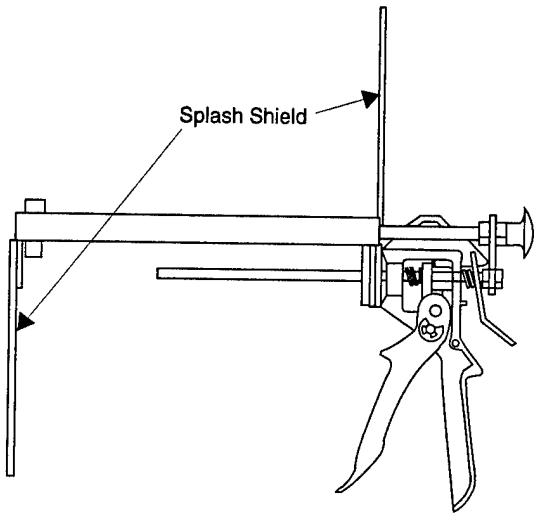


Fig. 2. Side view of foam dispensing gun showing added splash shields.

TABLE II.
Other Foam Materials Evaluated

Material designation	Manufacturer	Reason not chosen
PDL 707-2	Urethane Technologies, Inc.	Lifts mines during rise and cure; surface appearance
PDL 707-3.5	Urethane Technologies, Inc.	Lifts mines during rise and cure
PDL 328-4 (regular)	Urethane Technologies, Inc.	Too slow to rise
Stathane 4802W	Expanded Rubber and Plastics Co.	Too slow to rise; pigment compatibility
Stathane 4804 NF	Expanded Rubber and Plastics Co.	Too slow to rise; pigment compatibility
Stathane 6603 WF	Expanded Rubber and Plastics Co.	Too slow to rise; pigment compatibility

Foam materials from Expanded Rubber and Plastics, Inc. were too slow to rise and showed compatibility problems with the colorants studied. This situation resulted in streaking and a roughened surface, indicating incomplete nucleation of the foam.

B. Foam Properties

The average compressive strength of the foam formulation selected varied from 59.1 to 83.1 psi (Table III), depending on the mixing method used and whether the foam was pigmented. These values, considered more than adequate for the intended application, met the program requirement of 25 psi.

Field tests also showed that as little as 1/2 in. of foam covering a pressure triggering pin on an M-16 mine was sufficient to prevent tripping the trigger when stepped on. Only after foam-encapsulated mines were removed from the ground and jumped on with both feet was it then possible to trip some triggering devices.

Table III shows that density values of the pigmented foam were slightly less than for the unpigmented material. The density of the unpigmented foam did not, however, vary significantly with the mixing method used. Compressive strengths of the pigmented foam were approximately 10 percent less than values obtained with unpigmented foam when both were dispensed using the static mixing nozzle.

While density was not significantly affected by the mixing method used, the compressive strength of unpigmented machine mixed samples was more than 20 percent greater than samples made using a single static mixing head nozzle to combine the foam components. This difference was due to better nucleation of the foam-generated carbon dioxide bubbles that create the foaming action and was aided when air was stirred in with the foam chemicals using the hand-mix and machine-mix methods. The static mixing head does not allow air into the chemicals as they travel down the nozzle.

The hand and machine mixing processes allow for better mixing because the nozzle permits only a limited mixing time as material is swirled through it. This behavior was demonstrated by attaching three nozzles end to end, extending to nearly 3 feet the mixing distance achieved using the static mixing process. Here, an intermediate compressive strength value was achieved. This experimental extension is not practical due to increased back pressure, resulting in excessive operator effort to dispense the foam. (The single-nozzle system is preferred because the operator is not exposed to the unreacted foam chemical components when using the dispensing gun.)

It was also noted that the interior areas of hand-mixed foam appeared to be less friable and more homogeneous than foam samples made using the static mixing head. Nevertheless, all specimens made in the laboratory and in field tests with any of the mixing methods evaluated provided more than adequate strength and durability for the foaming application.

C. Colorant Selection

Table IV shows the dye and pigment colorants studied for this program. Dyes, being liquid in form, tend to be more compatible with urethane foam chemicals than powder pigments. In general, however, the dye colors are not as bright, and they are not ultraviolet (UV) fluorescent.

In all cases, colorants were added first to the polyol component (Part B) by mechanical mixing. Colorants were not added to the isocyanate portion in advance to avoid introducing moisture into this component (which reacts with water as part of the overall foam reaction). Some settling of the colorants occurred in all formulations with the various foam materials tested. The R6-OR9014 pigment selected showed the least settling while providing the material compatibility and bright orange-red color desired. This material also provided UV fluorescence for nighttime observation.

High concentrations of colorant increased the viscosity of the foam chemicals beyond that acceptable for proper dispensing. A 7.0 percent concentration of the R6-OR9014 pigment, selected as optimum, was added to the polyol as a 15 percent concentration. When the polyol plus pigment and isocyanate components of the foam were mixed, the effective concentration was 7.0 percent by weight.

TABLE III
MECHANICAL PROPERTIES OF CURED PDL 328-4 FAST FOAM

Property measured	Mixing method			
	Static mixing nozzle	Three ganged static mixing nozzles	Hand mixing	Machine mixing
Density (lb/in^3)				
Pigmented	3.9	— [c]	—	—
Unpigmented	4.3	4.1	4.3	4.3
Compressive strength [a,b] (psi)				
Pigmented	59.1	—	—	—
Unpigmented	65.8	72.7	82.8	83.1

[a]Room temperature test values determined in accordance with ASTM D1621.

[b]Program requirement is 25 psi

[c]Not tested.

TABLE IV
SELECTED COLORANT (R6-OR9014), SHOWING BEST COMPATIBILITY AND LEAST SETTLING. OTHER COLORANTS EVALUATED ARE SHOWN.

Colorant type	Material designation	Manufacturer
Pigment	R6-OR9014	Magruder Color Co. (Radiant Div.)
Pigment	P7-OR0624	Magruder Color Co.
Pigment	TI-OR6714	Magruder Color Co.
Pigment	GF-OR0014	Magruder Color Co.
Pigment	P7-OG0623	Magruder Color Co.
Pigment	P7-OR9013	Magruder Color Co.
Dye	Reactint x52	Milliken
Dye	Reactint x38	Milliken

Color stability was tested by exposing cured foam samples to bright summertime Southern California sunlight for 6 weeks. At the end of that time period, the foam had turned a darker reddish-brown color. This color, combined with the foam shape, was still readily distinguishable in the field. Field tests at Ft. A.P. Hill under overcast conditions showed no color change after 3 weeks of outdoor exposure. It was noted that UV fluorescence was no longer apparent after 1 week's exposure to sunlight.

D. Wet Surface Test Results

Tests of the selected foam in wet conditions were performed to examine the effects of rain and high humidity on foam application.

1) Spray mist test: Foam was dispensed while spray mist from a water bottle simulated rain. No adverse effects on foaming action, hardening, or curing were noted.

2) Water surface test: Foam was dispensed into a 1/8th-in. layer of water in a metal tray around a simulated mine periphery. Being heavier than water (in liquid state), the foam material sank below the surface of the water and flowed away from the mine. The balance of the foam was applied to the mine surface. While the foam rose normally and adhered to the mine, some voids were created beneath the surface.

Dispensing took about 1 minute. After about 25 to 35 seconds, the foam around the mine began to rise. In about 3 minutes the foam rose to a height of about 4 in. The foam was tack-free at 4 minutes and hard in about 5 minutes. It was concluded that the water did not prevent the foam from expanding or curing. Further, if the foam must be dispensed onto a semi-submersed mine, a dam or ring of material around the mine would help keep the foam in the area where it is needed. This effect would be especially important if the mine was on a slope where the foam chemicals could run off prior to expanding.

E. Ft. A.P. Hill Product Demonstration

On November 16 and 17, 1995, the Hughes-designed mine marking foam was demonstrated at Ft. A.P. Hill. Several foam product kits were used on a variety of exposed land mines (Table V).

TABLE V
MINE MARKING FOAM USED SUCCESSFULLY BY SPECIAL FORCES PERSONNEL ON VARIOUS MINES AT FT. A.P. HILL

Mine type	Number of mines tested with foam
M-16	8
PMD-6	4
Vs Mk 2	6
Vs-50	3
Ts-50	1
M-14	3
PMN	1
M-3	1
Valmira 69	1
TMD 44	1

Ambient temperature during the demonstration was between 30 and 50°F. Foam cartridges were stored overnight at temperatures between 20 and 30°F prior to the demonstration. The cartridges stayed quite cold because the plastic cartridges and the foil pouch containers insulated the foam chemicals. Under these conditions, the following observations and conclusions were made:

1) The foam was successfully mixed and dispensed from the gun during periods ranging from 1 minute 50 seconds to 3 minutes 45 seconds, and began to rise from 1 minute 30 seconds to 3 minutes thereafter (Fig. 3). The foam was hard after 4 to 11 minutes total time following dispensing. It is difficult to extrude foam chemicals using the dispensing gun when temperatures are below 50°F.

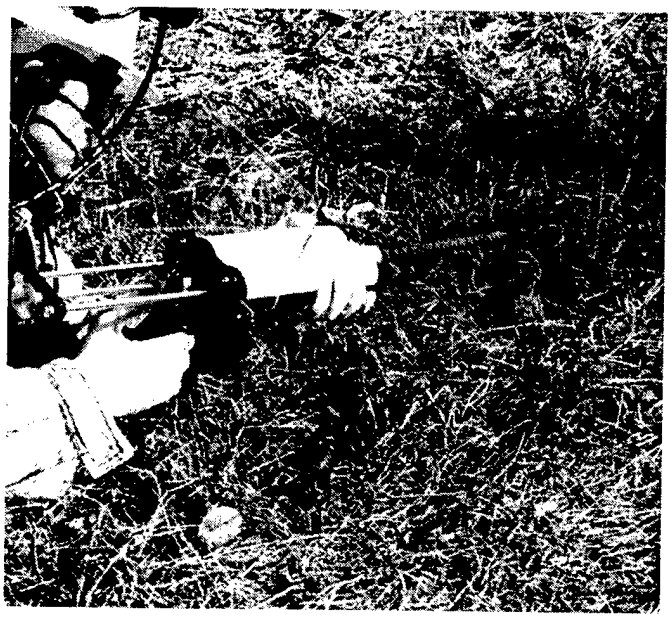


Fig. 3. Operator uses dispensing gun to mix and apply foam.

2) The foam adhered well to most metal and plastic surfaces, even when the surfaces were cold, wet, and dirty (Fig. 4). While the foam did stick to some wooden box mines (Fig. 5), it appeared that the amount of mine surface exposed prior to applying the foam was more critical for this type of mine. (The foam pulled away from one of four PMD-6 and one large anti-tank mine when attempts were made to pull these mines from hard, wet earth.) Mines having exposed tripwire mechanisms required minimal unearthing. Tripwire mechanisms provide a good "handle" for the foam to grab onto. They prevent the mechanism from setting off the fuse and allow the mine to be pulled from the ground by a length of rope embedded in the foam which acts as a lanyard. While it would never be done in practice, it was shown that tripwires could be used to pull out form-encapsulated M-16 mines buried in the ground without tripping the mine's fuse.

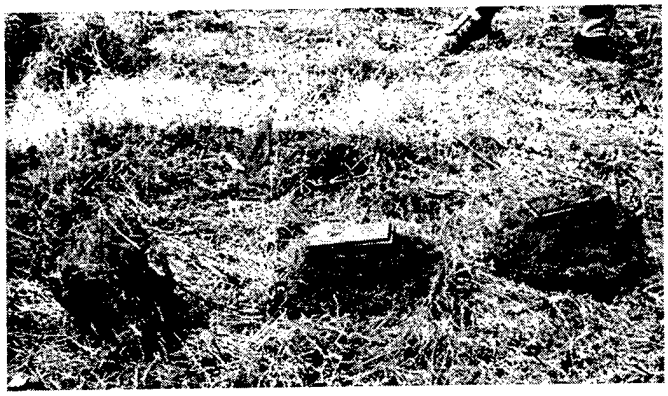


Fig. 4. Foam adhering to mine allows removal from hard-packed soils.



Fig. 5. Foam adhered well to some wooden box mines with wet and dirty surfaces.

3) The foam color was excellent; the brilliant day-glo orange-red (Fig. 6) was easily visible from over a 100 yards away. It was demonstrated that the foam fluoresced in a darkened room when exposed to UV light.

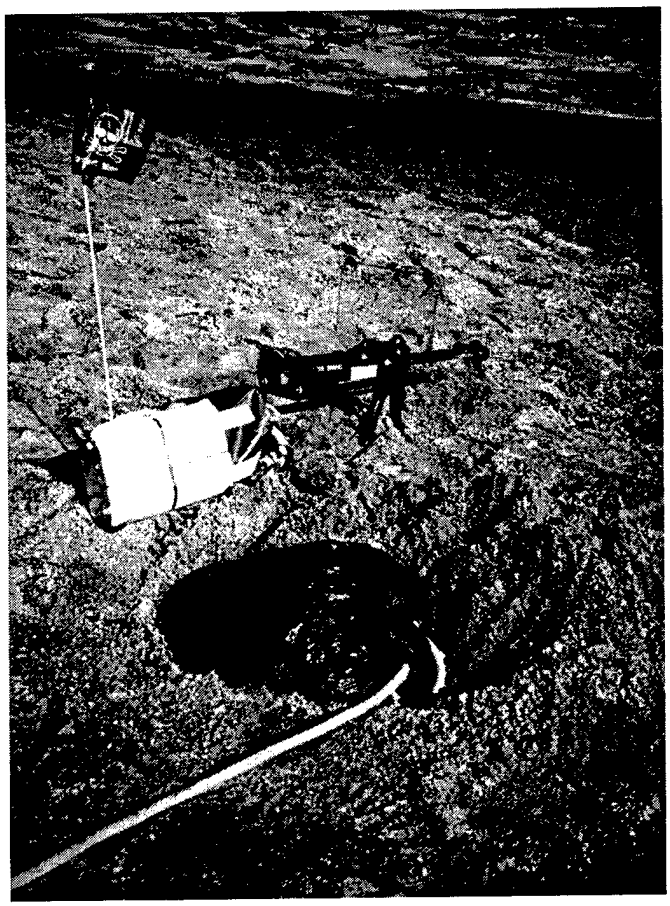


Fig. 6. Brilliant day-glo orange-red colored foam makes identification easy.

4) Because of the difficulty of using the dispensing gun at cold temperatures, it was decided in some cases to not use the mixing tip and gun for mixing, but rather to use the mixing tip to push the cartridge contents into the foil kit bag (Fig. 7), stir/mix the foam chemicals in the bag, and pour the mixed liquid onto a mine (Fig. 8). This approach worked very well, being actually faster than using the mixing tip and gun. The Special Forces personnel liked the consistency and texture of the bag-mixed foam as well or better than the foam dispensed from the gun. They had no objection to using the bag as a mixing pouch, and suggested that it be a viable option for inclusion into the kit's instruction sheet.

5) Special Forces personnel used the latex gloves (Fig. 9) packaged with the foam kits without any difficulty or objection. The gloves successfully kept the foam chemicals off their hands at all times during the process.

6) It was observed that improvements are needed with the static mixing nozzle, dispensing gun, cartridges, etc., to make



Fig. 7. Alternate method speeds mixing and dispensing of foam in cold weather.



Fig. 8. Alternate method reduces mixing and dispensing time in cold weather to less than 1 minute.

dispensing easier at low temperatures, and to inject air into the foam chemicals to improve the foam's appearance, increase the volume of the expanded foam, and possibly improve the foam's uniformity.

7) If it is desired to remove the mine using a length of rope embedded in the foam as it rises and cures, the following elements must be considered: the shape of the area dug out around each mine varies, depending on the size of the mine, the condition of the earth (e.g., sand, mud, clay), and the amount of mine mechanism exposed that can be encapsulated and entrapped by the foam (Fig. 10). For anti-personnel



Fig. 9. Special Forces personnel use latex gloves packaged with kits to ensure foam chemicals do not touch hands.



Fig. 10. Rope lanyard frozen in foam is used to pull mines from ground.

mines with smooth surfaces such as the PMD-6 box mine, approximately one-half the depth of the mine should be exposed around its periphery from 1 to 2 in. away from the mine. For smaller plastic TS-50 or VS-50 mines, only the top one-third of the mine need be exposed. For M-16 mines with tripwire fuses, only the fuse and tripwire need be exposed to the foam.

8) To prevent lifting of a mine during the foaming operation (which might set off anti-disturbance triggers), the mine should not be completely exposed. If that occurs, the foam chemical may wick under the mine and lift it.

9) Explosive (shaped) charges are capable of penetrating the foam and detonating mines marked by and covered with the cured foam (Figs. 11 through 13).

10) If a "mix-in-the-bag" package is created, the static mixing head should be replaced with a simple wooden mixing stick, and the dual mixing cartridges replaced with a simpler container. This approach would likely reduce the cost of each kit. Alternatively, Special Forces personnel suggested

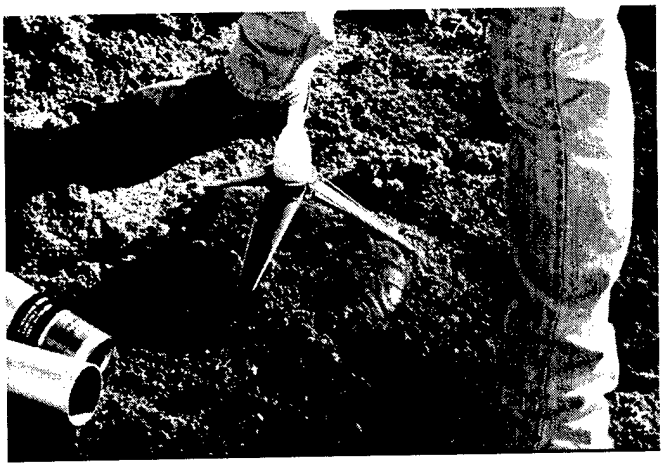


Fig. 11. Shaped charge placed over foam-encapsulated PMD-6 can detonate a mine.



Fig. 12. Foam does not inhibit mine detonation.

creating a single cartridge with a separation diaphragm and mixing rod that could be carried in the pouches of a soldier's vest.

11) Mines captured by the foam can be dragged a short distance (Fig. 14) without being dislodged. In one test with a Vs-50 and a Ts-50 mine, one of the two was dislodged from the foam while being pulled across flat ground for about 50 feet using a rope lanyard frozen in the foam (Fig. 15). Neither mine was triggered by this dragging test.

12) The foam was capable of distributing loads applied to AP mines in the places where they were exposed, and their tops or triggering mechanisms were completely covered by foam. In one or two cases, however, it was possible to trip the mines once they were pulled from the ground and then jumped on with one or both feet or where a pressure trigger finger was not fully encapsulated. Otherwise, all of the

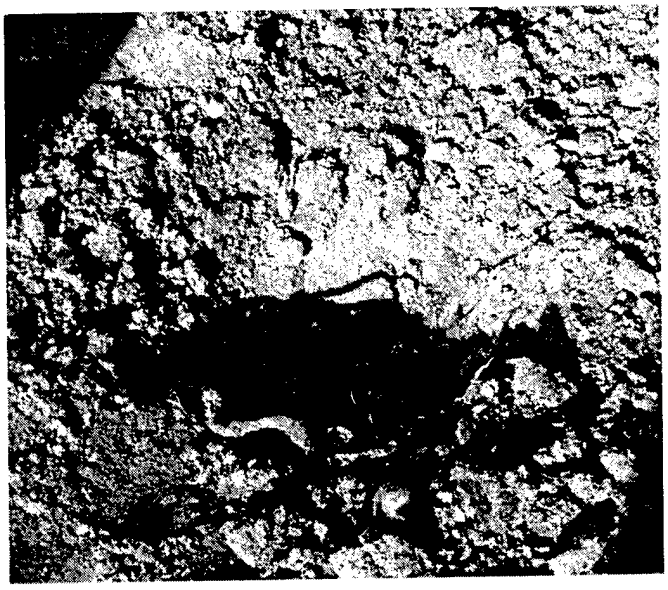


Fig. 13. Only colored residue and rope remain following mine destruction.



Fig. 14. Encapsulation by cured foam allows mine to be pulled by lanyard for short distances.

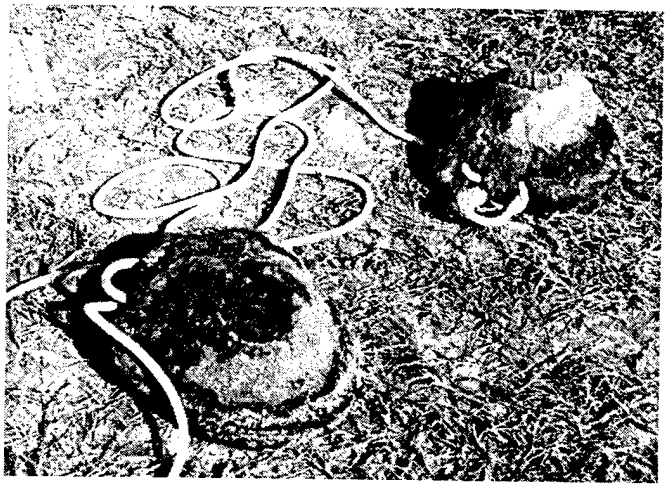


Fig. 15. Degree of adhesion of cured foam to mine varies with that portion of the mine encapsulated.

foamed mines were strong and rigid enough to withstand being stood upon without being tripped.

13) No separation of the foam dye was observed in the cured foam. The foam was uniform in color in all cases.

14) To mark a mine and to aid in the depth perception of a remote-controlled, robotic, mine-locating-and-recovery machine, a large "X" of the foam material was applied over an anti-tank mine and the surrounding area (Fig. 16). This method provided the necessary visual cues, and the robot operator said it was an excellent aid in guiding him to dig up and capture the mine properly (Fig. 17).

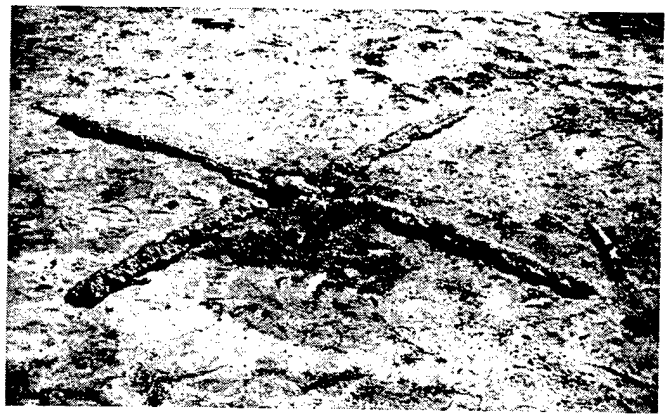


Fig. 16. "X" pattern of foam marks mine.



Fig. 17. "X" pattern of foam aided robot operator's depth perception when using remote-controlled mine excavation equipment.

IV. Conclusions

All program objectives were successfully met with the development and delivery of mine-marking foam and associated dispensing equipment. Even in inclement weather conditions, the foam material performed well. In addition to marking mines, it was shown that the foam could disable a variety of mine tripwire mechanisms. Also, it was demonstrated that the adhesion of the foam to most mines was quitestrong, even under less-than-ideal conditions. The ability to create a long-distance "handle" for removing mines from the ground by embedding a piece of rope in the foam was also demonstrated.

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The Development of a Multimedia Electronic Performance Support System for Humanitarian Demining for the Proceedings of Technology and the Mine Problem Symposium

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Abstract - Any effective humanitarian demining training and operational support system must provide on-demand access to all the resources that are needed to perform a task, solve a problem, train and inform indigenous personnel and support the overall management of the demining program. The use of a multimedia electronic performance support system (designed for in-country field use) can be an extremely cost effective tool in being able to generate performance and training support at the moment of need. Today's technologies allow for compact storage of vast amounts of information, full motion video, graphics and multi-language audio, all available in a variety of output formats, rugged enough for use in the field. Properly designed and packaged, these systems can significantly improve the efficiency and safety of humanitarian demining operations.

INTRODUCTION

Currently there are an estimated 110 million landmines scattered throughout 64 countries. Landmines maim or kill an estimated 500 people per week [1]. The United Nations projects that if the use of landmines were stopped immediately it would take 1,100 years and $33 billion dollars, at the current rate to clear, those already in place [2].

The statistics associated with reported landmine casualties are staggering. The landmine problem has resulted in arrested economic development that, if not effectively mitigated, will result in continued economic devastation and migration to neighboring countries with already fragile infrastructures.

Currently there is a major international thrust to develop demining equipment and techniques capable of augmenting the demining effort. To support this effort, the Night Vision and Electronic Sensors Directorate at Ft. Belvoir has developed over 30 items to assist in the mitigation of the landmine crisis. One of these initiatives is the Demining Support System (DSS). The purpose of this paper is to discuss the rationale behind the development of the system, to discuss design considerations, and to provide an overview of the systems content.

REQUIREMENTS

As part of the humanitarian demining program there are provisions to leave behind developed solutions for continued in-country use. The Office of the Deputy Assistant Secretary of Defense for Humanitarian and Refugee Affairs determined the most successful program in terms of cost feasibility is one that trains to promote an indigenous capability in countries affected by landmines so that they can eventually solve their own landmine problems. The skills that must be learned include: minefield reconnaissance, locating mines, reporting mines, mapping minefields, destroying mines, managing the mine-removal operation, launching a mine-awareness campaign, addressing the consequences of landmines on public health, implementing first aid and follow-up treatment, and addressing the psychological impact of mine-related injuries.

DEFINITION OF ELECTRONIC PERFORMANCE SUPPORT SYSTEM

To accomplish these diverse tasks and meet the needs of the trainer, a different performance technology and media approach are required. The technique capable of supporting the requirements is the Electronic Performance Support System (EPSS). The goal of an EPSS is to provide whatever is necessary to generate performance and learning *at the moment of need* [3]. This can also be referred to as *on-demand, just-enough*, or *just-in-time* training.

There are several working definitions for an EPSS that range from "...the electronic infrastructure that captures, stores and distributes individual and corporate knowledge assets throughout

the organization, to enable individuals to achieve required levels of performance in the fastest possible time and with a minimum of support from other people." [4] to "...[being] universally and consistently available *on demand* any time, any place, and regardless of situation, without unnecessary intermediaries involved in the process." [3, p. 34] For our purposes, we will define EPSS as the integration of available technologies (human performance and computer) to facilitate the accomplishment of a desired outcome. In this case, the desired outcome is for countries affected by landmines to conduct successful demining operations.

WHY MULTIMEDIA?

An immediate reaction to the system regarding a multimedia-based platform is normally, "Multimedia for demining? The people who developed this can't possibly be in touch with reality. Demining is low tech and requires a low tech approach....."

Based upon an analysis of the ARSOF training requirements, target audience (deploying trainers to host nation deminer), and currently utilized training methodologies, multimedia was selected as the platform to deliver demining training materials. The utilization of a multimedia platform provides the trainer the ability to give customized and *just-in-time* training for diverse target audiences and locations.

The design of the DSS was derived from the data obtained through interviews of mission planners, trainers, and medics, and a review of field manuals and after action reports. The analysis yielded the following desired system characteristics.

Visual based - training based on visuals addresses the literacy level of the indigenous populations.

Language support - audio narrations provide an immediate, consistent approach to the transfer of information in the native language of the trainee.

Content based - preselected and organized visual and audio materials provide a baseline for training in demining techniques, medical procedures, and mine awareness.

Tool based - an option to modify or add demining, medical or mine awareness material addresses the unique circumstances encountered in the field.

Flexible- The user is in the best position to decide what form of output (poster, printout, video, presentation, audio) most suits the situation. A program that supports all five media options simultaneously provides a synergistic approach required to support multiple training options.

Supportable - the use and support of technology must not hinder mission deployment.

To accomplish these tasks requires that a system possess certain attributes. First, it must have a large and flexible data storage capability and play multiple CD-ROMs. Second, the ability to use full motion video is needed. Video is the only media that permits the introduction of training and informational materials in aural, verbal, visual, and kinesthetic imagery [5]. This has direct implications for the selection of informational materials to be included on the system and instructional design considerations. Third, it must have the ability to incorporate hardware into the system that permits modifying and adding materials to the base system instructional materials. This permits localized customization of training and mine awareness materials. Fourth, it must be expandable without changing the base components.

A multimedia system can support these characteristic by providing flexible software and hardware configurations that facilitate the integration of voice, sound, image, and motion. The enhanced technology of multimedia enables presentations to take on a more realistic appearance than systems that provide only still images without voice, sound, and motion [6].

MODULE DEVELOPMENT

An instructional systems design (ISD) methodology was used to develop the content of the systems module. The ISD process consists of five phases: analysis, design, development, implementation, and analysis. The analysis methodology used three distinct phases. First, relevant literature was examined to identify mission planning formats and programs of instruction (POI). Second, we interviewed ARSOF subject-matter experts who have experience in mission planning, demining operations, mine awareness and medical procedures. The interview formats were designed to elicit experience and knowledge through the retelling of specific incidents to provide an idea of how the mission specialist performs the tasks. Third, we identified the POIs employed by Special Operation personnel on missions similar to what can be expected to be found during demining operations.

The analysis results were presented in a survey format to subject-matter experts at Ft. Bragg and Ft. Campbell. The survey participants reviewed the list, verifying the topics suitability and identifying their importance to a humanitarian demining mission. The result of this analysis determined that the systems modules should consist of demining techniques, medical training, and mine- awareness.

SYSTEMS FUNCTIONALITY AND EQUIPMENT

The DSS design does not preclude a low-tech implementation of training materials. It enhances the instructional capability of the ARSOF trainer by providing the ability to present instruction using different media, depending on the situation and student audience. Although the system is capable of delivering instructional materials in audio and video modes, the primary delivery media is print.

The system can display, print and edit lesson plans, field evaluation cards, graphics for heat press cloth transfers, handouts, labels, and posters, in support of training and mine awareness activities. The inclusion of a scanner and digital camera greatly enhances the capabilities of the system by providing a means for the SF trainer to rapidly and easily develop complex training materials produced for a specific purpose which was not foreseen during predeployment planning.

Composition of the Demining Support System

17" Mitsubishi rackmount, touch screen monitor

Speakers/Amplifier - Fostex 630LB

Fieldworks 766P Laptop - Pentium 166, 4X CD-ROM, 32 MB RAM, 1 gig hard drive

CD-ROM Jukebox (7 Disk)

Scanner - Logitech Page Scan Color

Digital Camera - Kodak DC-40

Color Printer - Canon BJ-70

Poster Printer - Encad Novajet

Heat Press - Basix

AC Line Voltage Regulator - Furman Line Conditioner

MODULE CONTENT

Each topic module is broken into discrete lesson modules. Based upon the media analysis, a lesson module may be in any combination of media (audio, video, or print) and capable of being presented in English and a selected language. These materials provide the continuity and consistency required to utilize the train-the-trainer methodology.

A brief explanation of each module is provided below.

Mission Planning & Management Guide

Provides immediate access to materials required for the planning and execution of a demining mission to include applicable references, equipment manuals (text and electronic manuals), forms and formats for reports and briefing.

Training

The courses in this module provide advanced training for individual skills topics from selected demining sources. The current available courses are the Combat Life Savers Course (CLS), Demining Course, and Communication Course.

Medical

Provides instruction on the treatment of landmine related injuries. The module contains information about Buddy Aid, provides a copy of the current Combat Life Savers Course, and current literature on topics related to landmines.

Mine Awareness

Mine awareness information printable on items such as scarves, T-shirts, ponchos, tote bags, or mine awareness posters. Cultural considerations have been included in the development of mine awareness materials that may be distributed as part of an in-country mine-awareness program.

MineFacts

A database that supports in the field access to pictures, animated images and detailed specification of landmines found around the world. An option is provided to create customized folders of landmine information, such as mines used in local areas. MineFacts has the capability of being used to create mine awareness materials.

Electronic Library

The library provides an on-demand source of materials for the maintenance and operation of demining equipment.

CONCLUSION

The Demining Support System is an Electronic Performance Support System which provides a useful tool to facilitate demining training. It provides references and training materials in text, graphic, audio, or video media while remaining flexible to the requirements of the on-site trainer. The tools provided permit the editing of existing materials and the ability to create customized

training materials. The DSS is modular and transportable, which permits rapid worldwide deployment to support the demining mission.

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LEXFOAM FOR HUMANITARIAN DEMINING

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Abstract - This paper describes the development of LEXFOAM® (Liquid EXplosive FOAM) from its invention as a novel low density explosive, to its successful application as an effective tool for "blow-in-place" demining. Explosives research using aerosol technology led to the development of LEXFOAM whose components are safely transported and stored as flammable liquids. These components are mixed on site to produce an explosive foam; this enhances safety, minimizes logistical problems and virtually eliminates the possibility of misuse of LEXFOAM by unfriendly forces. Palletized (440 lb. capability) and Backpack (30 lb. capacity) Delivery Systems facilitate the mixing and delivery of LEXFOAM in a variety of situations which may be encountered during humanitarian demining operations.

Instrumented experiments have determined the detonation velocity, as well as the detonation and in-ground pressures for a number of LEXFOAM configurations. Based on these data, and results of trials against a wide variety of Anti-Personnel (AP) and Anti-Tank (AT) mines, the optimum LEXFOAM density and foam layer thickness have been found to be 0.5 g/cc and 2 in. respectively. The mines tested include bounding fragmentation, pressure operated and blast resistant AP mines, as well as pressure operated, and pressure operated/blast resistant AT mines. The results demonstrate that LEXFOAM is 100 percent effective in neutralizing many different mine threats.

LEXFOAM and LEXFOAM Delivery Systems have been shown to be safe, easy to use, cost effective and proficient tools for ordnance demolition. Moreover, safety and simplicity make these systems particularly suited for use by indigenous operators during humanitarian demining operations. Finally, project managers can rest assured that LEXFOAM, unlike conventional high explosives, is not likely to be misappropriated for misuse in military or terrorist operations.

I. INTRODUCTION

A. The Landmine Problem - Background

Humanitarian demining is a term coined for the disposal, or "neutralization," of anti-personnel land mines and other explosive devices that threaten civilians and national infrastructures. These devices cause immense human suffering world-wide, as well as major economic losses and political instability in third-world countries. Many devices are deployed as terrorist weapons in markets, roads, waterways and on farmable land to terrorize and destabilize governments and economies. There are currently over 250,000 people who have been disabled by land mines in the world. The majority of people killed or maimed by land mines are women, children and elderly individuals. The landmine problem results in serious economic costs to industrialized nations, in the form of humanitarian, economic and military aid costs, including lost sales and markets. Approximately 100 million mines are now deployed in 64 countries, and additional mines are being deployed much faster than they are being neutralized [1].

B. Landmine Countermeasures - Detection

Metal detectors, hand-held probes, and military mechanical breaching equipment are currently the most effective tools to detect and clear land mines and unexploded ordnance. There are many advanced sensor technologies in various stages of research and development which can be applied to detection and clearance. The sensor technologies include infrared, ultra-violet, ground penetrating radars, microwave, photon backscatter, nuclear or thermal neutron analysis, lasers, or a combination of these sensors.

This paper will not address detection of land mines, but rather, will focus on neutralization (destruction) of land mines or unexploded ordnance by "blow-in-place" sympathetic detonation techniques. The destruction of mines in place is rapidly becoming the accepted method of permanently neutralizing land mines and unexploded ordnance.

C. Landmine Countermeasures - Neutralization

Most techniques in humanitarian demining are borrowed from equipment, materials, and removal procedures established by military doctrine intended primarily to "breach" minefields for or during combat. A Quality Assurance clearance level of 95% is generally acceptable in military operations, however, this level approaches 100% for humanitarian demining.

The countermine materials and equipment used for military breaching, and at times in humanitarian demining, include mechanical plows, flails, rollers, line charges, and solid explosive charges such as C4 and TNT. Each of these methods has its drawbacks for humanitarian demining, including effectiveness and/or cost.

In humanitarian demining, it is generally accepted that upon detection of the landmine, "blow-in-place" techniques will be used to neutralize the threat. This is generally done with high explosives (C-4, TNT block) or by directed energy (shaped charge attack). The use of these techniques also has its drawbacks, including: the costs associated with the logistics of handling high explosives; the possible safety factors involved with placing explosive directly on an exposed landmine (no standoff); and the dangers associated with security concerns in many of the third world countries, such as theft by terrorist organizations. The following sections present information regarding the use of a novel distributed explosive technology based on the use of a liquid explosive foam - LEXFOAM*, for use in humanitarian demining.

II. The LEXFOAM Solution

A. History of LEXFOAM

The detonation properties of solid high density explosives (≥1.0 g/cc) have been extensively investigated. These types of explosives have detonation pressures of several hundred kbar and detonation velocities up to 9 km/s. At the other end of the spectrum are fuel-air (or oxygen) explosives whose detonation pressures are less than 20 - 50 bar with detonation velocities less than 2 km/s. Explosives systems covering the entire range between these two extremes are theoretically possible, however only a few such systems have been studied experimentally.

The most straightforward method of varying the detonation pressure and velocity is to vary the density of high explosive loading. Tulis has shown that clouds of high explosive dusts dispersed into air can produce detonation pressures (100 bar) well in excess of those produced in standard fuel-air configurations [2]. The dispersal of explosive dust clouds with uniform cloud consistency, however, is fraught with experimental difficulties.

A potentially more effective method of producing explosive systems with low loading densities and uniform detonation properties is to disperse the explosive in a porous foam matrix. An alternative method would be to produce a foam from a liquid explosive, or from a liquid which would have explosive characteristics in foam form.

Several researchers have investigated the use of explosive-impregnated polyurethane foams [3-8]. The detonation properties reported for each type of foam included detonability limits, and (in some cases) theoretical/experimental detonation velocities and pressures as a function of density. However, in at least one case, the investigators found that the viscosity of the urethane/explosive mix precluded efficient dispersal of the foam as a mine neutralization technique [8].

Pool investigated a foamed liquid explosive involving a mixture of nitromethane and metal stearate surfactants [9]. This composition was whipped into a semi-stable foam with a foam density of 0.5 g/cc. It was reported that the foam drainage characteristics were rather poor. As well, Alford has described a liquid foamed explosive, produced using aerosol technology [10]. The foam was based on an aqueous solution containing inorganic nitrates and PETN. It should be noted that this composition, due to the PETN content, was classified as an explosive (UN 1.1D). This foam was known by the trade names FOAMEX or PRIMAFOAM (depending on the country of manufacture/sale).

The preceding (detrimental) factors have resulted in the development of a liquid explosive foam - **LEXFOAM***. This nitroparaffin-based foam is based on the use of aerosol technology and emulsion science. The energetic component comprises approximately 90% of the foam material.

The use of a nitroparaffin-based explosive foam offers advantages not found with other explosive technologies including the advantages of safety and cost. LEXFOAM Stock Solution (from which the foam is produced) is classified as a flammable liquid - Class 3, UN 1261. This offers significant logistics cost savings, as the precautions necessary for the shipping and storage of high explosives are eliminated. As well, the BACKPACK and PALLETIZED foam dispersal systems are designed to be easily used by trained personnel in field applications: the training can be accomplished in a minimal amount of time. Finally, LEXFOAM has consistently neutralized a wide variety of mines in a variety of test and evaluation situations, with success levels consistently approaching 100%. The following sections outline: the detonation properties of LEXFOAM; the countermine successes and ongoing database development associated with this technology; a description of the dispersal systems designed to facilitate the use of the foam in humanitarian demining applications; and a discussion of LEXFOAM countermine techniques.

B. LEXFOAM Detonation Properties

This section summarizes the results of an investigation to experimentally determine the detonation pressures as a function of foam density, and to correlate these results with

measured in-ground pressures and impulses as a function of foam density and foam layer thickness.

The velocity of detonation (VOD) of the LEXFOAM was determined using either the continuous resistance wire technique, or piezoelectric pin (point-to-point) techniques. Piezoresistive (carbon) and piezoelectric (Polyvinylidene difluoride-PVDF) gauge elements were used to determine the detonation pressures for both incident (sweeping) and transmitted shock loadings. In-ground pressures and impulses were measured using either modified Kulite gauges and/or column based stress (CBS) gauges developed by Waterways Experiment Station (WES), in conjunction with "flat-pack" PVDF gauges developed by DYNASEN [11-13].

Incident and transmitted detonation pressures were measured for foam layer thicknesses of 2.5 and 5 cm, with associated foam densities of 0.2 and 0.4 g/cm^3. As well, in-ground pressures and impulses were determined for these foam configurations. In-ground pressures were also determined for 2.5 cm and 5 cm thick layers of LEXFOAM having foam densities of 0.25 and 0.5 g/cm^3.

Figure 1 illustrates the measured detonation velocity as a function of foam density. Figure 2 shows measured incident and transmitted detonation pressures, and compares these pressures with calculated pressures from three different equations used to approximate detonation pressures. It is clear that the relationship $P = \rho_o D^2/4$, where ρ_o is the initial foam density and D is the measured VOD, most closely approximates the detonation pressures for the foam system, particularly at the lower foam densities. Furthermore, it is apparent that the transmitted detonation pressures are of the order of twice the incident detonation pressures. Duvall has noted that, depending on the target material, this phenomenon can readily occur for shock waves impacting normal to a target [14]. This increase in transmitted detonation pressures has ramifications for mine neutralization; specifically that the LEXFOAM should be located and initiated such that the detonation wave impacts the mine with a transmitted shock for optimum effect.

It should be noted that there was minimal difference in measured incident detonation pressures for both 2.5 cm and 5 cm thick layers of LEXFOAM, and that all transmitted detonation pressures were measured using 5 cm thick layers of foam at the associated pressure gauges.

Figures 3 and 4 outline the measured in-ground pressures and impulses, for various foam layer thicknesses and foam densities. Each datum represents an average of 3-5 measurements. The following trends are apparent:

i) for a given foam density, increasing the foam layer thickness increases the in-ground pressures at a given gauge burial depth;

ii) for a given foam layer thickness, increasing the foam density increases the in-ground pressure measured at a given gauge burial depth;

iii) similar in-ground pressures for different foam densities can be attained by adjusting the thickness of the foam layer. For example, a 5 cm thick layer of foam, having a foam density of 0.25 g/cm^3, will generate similar in-ground pressures (at gauge burial depths of 20-30 cm) as a 2.5 cm thick layer of foam having a foam density of 0.5 g/cm^3.

It is clear that 5 cm thick layers of LEXFOAM, for a given foam density, result in higher pressures at increased gauge burial depths than 2.5 cm thick layers of foam. This is due to the increased impulse associated with the thicker layer of foam. Duvall has observed this behavior [14]. Measured in-ground impulses at different gauge burial depths remain relatively constant for a 5 cm thick layer of foam. A 2.5 cm thick layer of foam exhibits decreased impulses at the deeper gauge burial depths.

C. LEXFOAM Countermine Successes

LEXFOAM has consistently demonstrated that it is an easily used, versatile, sprayable foam explosive material able to neutralize anti-personnel (AP) mines, anti-tank (AT) mines, and unexploded ordnance. The method of neutralization involves either: sympathetic detonation of the main explosive charge or fusing mechanism; function of the fuse and mine detonation; or mechanical destruction of the mine/fusing mechanism. Using these criteria for success, LEXFOAM has proven 100% effective as a mine neutralization technology in several series of field trials for both commercial and government clients. Table I outlines a list of land mines and unexploded ordnance successfully destroyed in unclassified government (U.S. Army Night Vision Directorate - Humanitarian Demining Program) trials and during commercial field trials in Kuwait following the Gulf War. It should be noted that the database of mines neutralized by LEXFOAM is continuously being updated.

III. LEXFOAM DELIVERY SYSTEMS

In a typical mine-clearing operation, LEXFOAM is deployed through a hand-held spray gun. The spray gun comes with a 2-foot long detonation trap assembly and two additional 2-foot long quick-disconnect extensions. This allows the user the option of selecting dispensing gun lengths of 2, 4 or 6 feet. In most instances, where a mine has been located, identified and checked for trip wires, a "close approach" has already been made and a short dispensing gun assembly may be acceptable.

In addition, LEXFOAM can be sprayed in large patches or in more defined patches over individual mines. A number of mines can then be explosively linked to each other by thin strips of LEXFOAM, or with detonating cord, allowing all linked mines to be destroyed using a single detonator.

Two separate, yet complementary delivery systems have been developed for the dispersal of LEXFOAM. The systems are designed to be loaded in the field with LEXFOAM STOCK SOLUTION; this solution is classified as a flammable liquid. Class 3, UN 1261, and therefore offers considerable advantages regarding safety, shipping, and storage considerations. It follows that the stock solution is an unlikely candidate for theft and terrorist use. In addition, LEXFOAM is environmentally friendly in that it is relatively non-toxic, biodegradable, and easily disposed of by burning or washing away with water.

The two methods of foam dispersal utilize backpack and palletized delivery systems. Details of these systems are outlined in the following sections.

A. Backpack Delivery System

The backpack system, when loaded, weighs approximately sixty pounds (27 kg). The backpack is ideal for spot coverage, for small jobs and for reaching mines or ordnance in locations that are difficult to reach accurately with the larger palletized system. The backpack is designed for operation by low skill-level indigenous personnel with minimal training. In brief, LEXFOAM STOCK solution is pumped into the backpack, followed by addition of a metered amount of liquid propane using pressurized nitrogen as the driving gas. The two components are mixed by inverting the backpack several times, after which the delivery system is ready for use. Figure 5 illustrates the backpack components and a fully assembled backpack.

The explosive foam can be sprayed directly on any expended ordnance to be neutralized. As an alternative, it can be applied directly on the ground over a known or suspected mine. The total elapsed time for filling the system and mixing, dispersing and detonating 15 kilograms of foam can be as little as 10 minutes.

B. Palletized Delivery System

The palletized delivery system is a 60-gallon (227 liter) vessel mounted on a steel skid for ease of transportation by a small trailer, 3/4-ton pick-up truck or other similar vehicle. The system includes: pre-measured containers of ingredients; a pumping system for transfer of the stock solution from a 55 gallon drum to the stainless steel pressure vessel tank; an agitator to mix the ingredients in the tank; nitrogen for pressurizing the system; and a hose, trigger and nozzle system including a detonation trap for safe dispersal of the pressurized foam explosive. The system also includes a power source, controls and various safety systems and features. The system is designed for operation by low skill-level indigenous personnel with minimal training. The loading procedures are similar to those employed with the backpack system, albeit on a larger scale. Figure 6 illustrates the Palletized Delivery System, with attached trailer and added Backpack units.

The Palletized Delivery System, with associated trailer, is designed to produce four 200 kg batches of LEXFOAM before the components need to be restocked. In addition, the palletized unit is also designed to load the previously described backpacks, three of which can be included with the palletized unit as part of the complete LEXFOAM delivery system technology. It should be noted that both the Backpack and Palletized Units can be immediately refilled and used to mix and disperse more foam, or they can be cleaned with water and stored for later use.

IV. LEXFOAM COUNTERMINE TECHNIQUES

A. General Considerations

Based on experimental data, countermine successes and field experience, a variety of different techniques have been developed to successfully neutralize land mines. In most cases, the optimum foam configuration comprises a 5 cm (2") thick layer of foam, with a foam density of 0.5 g/cm^3. In conjunction with these parameters, the experimental data have demonstrated the importance of the following criteria:

i) If the mine is exposed, a layer of foam should be placed against the mine, with the detonator inserted at the opposite end of the layer. This ensures proper "run-up" to full detonation and subsequent impingement of a transmitted shock wave for maximum pressure transfer.

ii) If the mine is buried, the foam layer should be dispersed on the ground such that one end of the layer covers the suspect mine and initiation is implemented from the opposite end of the layer. Again, this insures full run-up and maximum detonation pressure imparted to the ground cover.

Once the foam is deployed, a blasting cap or a detonation charge can be placed at the appropriate location in the foam and triggered to detonate the entire foam layer. Detonation of the foam will reliably induce sympathetic detonation or destruction of surface ordnance and exposed mines. Buried mines which are fused and armed are reliably functioned, including mines buried at depths down to 10 inches. (Depending on the fuse type, mines have been initiated at even greater burial depths.)

It should be noted that most demining practices involve partial exposure of the mine for threat identification purposes.

Any mines, ordnance items or other explosive devices detonated by the foam may create craters in the ground and/or produce shrapnel and other potentially dangerous side effects. Therefore, practical safety precautions, including safe stand-off distances and personnel protection must be taken when detonating the foam.

A dispersed layer of foam, in the absence of other explosive devices, will not create craters and will generally have a trivial effect on the ground surface. Typical effects are limited to an approximately 5 cm (2") compression of the soil surface. The amount of compression which occurs depends on the soil composition and moisture content. The compression effect on paved surfaces such as roadways or runways of the order of fifty percent less than that induced in soil.

In addition, if it is decided not to detonate the foam for any reason, it can be neutralized with water or left to decompose into harmless and environmentally friendly by-products. This process will occur naturally over a period of hours, depending on ambient temperature and moisture conditions.

B. Specific Examples

Although the preceding criteria for use of LEXFOAM should generally be adhered to, as with all field applications actual demining scenerios are developed based on the experience of the deminer. This section outlines several examples of the use of LEXFOAM against selected AP mines, some of which are notoriously difficult to neutralize in-situ.

Most mine clearance organizations now insist on in-place destruction of land mines to simplify training and create clear, unambiguous drills. However, successful in-place destruction is not as simple as it may seem, and there are many situations were conventional explosives (such as TNT and C-4) meet their limitations. The unique properties of LEXFOAM offer practical solutions to these problems. The following examples are chosen to represent circumstances which generally occur in minefields throughout the world.

The **PROM-1** bounding fragmentation mine, illustrated in Figure 7(A), is designed to be buried with only the pronged fuze above the ground. It can be initiated either by pressure or tripwire, and utilizes a small charge to deploy to a height of approximately 0.7 meters, followed by detonation of the main charge. The side wall is made from thick steel to enhance fragmentation, but the thinnest and most vulnerable part of the casing, and therefore the ideal place for explosive attack, is the rounded shoulder. Attacking the PROM-1 using a demolition block of high explosive presents problems in that the block cannot easily be placed on the shoulder of the mine due to the proximity of any tripwires. This situation is shown in Figure 7(B). As well, the block does not have good contact with the rounded shoulder of the mine. This results in the block having to be placed against the body of the mine, which results in having to clear dirt from the side of the mine, increasing the risk of activating an anti-disturbance device. The position of the detonator will result in a incident shock wave transmitted to the mine, a situation which is not ideal from imparting significant pressure through the thick steel wall casing.

A more satisfactory, and less dangerous technique would be to attack the PROM-1 using LEXFOAM. This situation is illustrated in Figure 7(C). Only the shoulder of the mine must be exposed, reducing the risk of accidental initiation. The foam follows the contours of the shoulder to achieve intimate contact. The detonator can be placed to give the optimum direction of initiation.

The **PMR-2A** fragmentation stake mine is generally mounted on a stake above the ground to optimize the mine's range and effectiveness. Initiation is almost always by tripwire. The main explosive charge is housed in the top two thirds of a thick steel body. To achieve successful in-place destruction, a conventional demolition charge must be placed adjacent to the mine body. Trying to position a charge off the ground and against the mine is clumsy, time-consuming and dangerous. In addition, achieving close contact of the demolition charge with the rounded mine body is also difficult, increasing the chance of only partial destruction. With LEXFOAM, there is no need to build a structure to support the demolition charge at the correct height. The foam adheres to the mine body, filling the grooves and contouring around the body to achieve intimate contact. A trail of the foam is then dispersed down the stake and on the ground to a convenient and safe initiation point, well away from the tripwire. The mine, and the explosive neutralization configuration, are illustrated in Figure 8.

Directional fragmentation mines of the **Claymore** type are almost always mounted above the ground to maximize the fragmentation range. Although generally supplied with legs mounts, the mines are often mounted (depending on the terrain) on trees up to on meter above the ground. The mine is usually initiated by either trip wire or remote command. Positioning a demolition charge adjacent to the mine is awkward, while working close to the tripwire represents a constant hazard. As demonstrated in Figure 9, LEXFOAM can be dispersed against any surface of the mine body and a trail run to a convenient and safe initiation point. If a trail of foam is neither possible nor desirable, a patch of foam may be dispersed against the top of the mine. In either case, detonation of the LEXFOAM will result in sympathetic detonation of the mine.

The **PMA-3** pressure operated blast mine represents a class of plastic mines which are difficult to detect and are designed to be blast-resistant. This mine is shown in Figure 10(A). The main explosive charge is housed in a small cavity at the top center of the mine body, and is surrounded by air-gaps and a resilient plastic casing as illustrated in Figure 10(B). A demolition charge placed beside the mine may not be able to detonate the explosive, with the result that the mine could be in a more hazardous condition. Placing explosive blocks on top of a pressure operated mine is widely regarded an unacceptable, for obvious reasons. Figure 10(C) shows how LEXFOAM can be applied directly above the main charge on the top center of the mine. The negligible weight of the foam means that only the top surface of the mine be uncovered.

Initiation of the foam destroys the mine by either fuse function or sympathetic detonation.

Figure 11 illustrates the concept of using LEXFOAM to neutralize more than one mine at a time, particularly when, as is often the case, AP mines may be found close together (clusters). If the mines are very close together, then the entire area can be blanketed with a 5 cm (2") thick layer of foam. An alternative would be to connect a number of patches of foam with either a trail of foam or with detonating cord.

It is apparent that the use of LEXFOAM as a mine neutralization technique is limited only by the deminer's experience and ingenuity. This factor, coupled with the clearly defined advantages of safety, cost and logistics, demonstrates the viability of LEXFOAM technology for humanitarian demining operations.

V. Summary

LEXFOAM has been tested by the U.S. Army and in field tests in Kuwait. These tests have demonstrated that LEXFOAM is an easily used, versatile, foam explosive material, offering stand-off capability (sprayable), with a >99% field-proven ability to sympathetically detonate buried, surface and above ground anti-personnel (AP) mines, anti-tank (AT) mines, and unexploded ordnance. As a result of LEXFOAM's 100% success rate in destroying a variety of mines in the November 1995 A.P. Hill, U.S. Army tests at Fort Belvoir, Virginia, the U.S. Army's Humanitarian Demining Directorate concluded that the LEXFOAM System is ready for immediate use, and has recommended operational deployment.

LEXFOAM delivery systems are safe, easy to use, cost effective and a proficient tool for ordnance demolition. Moreover, safety and simplicity make this system particularly suitable for use by indigenous operators during humanitarian demining overseas. Finally, project managers can be assured that LEXFOAM, unlike conventional high explosives, does not lend itself to misuse by terrorists or anti-government groups.

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Device Name	Origin	Type of Mine or Ordnance
Valmara 59	Italy	Bounding fragmentation anti-personnel (AP) mines
Valmara 69	Italy	with thick sidewalls, usually tripwire operated.
M16	USA	"
OZM-72	Russia	"
Type 69	China	"
M14	USA	Pressure operated AP blast mines
PMN	Russia	"
PMD-6	Russia	"
Type 72	China	"
VS-50	Italy	Blast resistant, pressure operated AP blast mine.
TS-50	Italy	"
M15	USA	Pressure operated anti-tank (AT) blast mine.
M19	USA	"
TM-57	Russia	"
TM-62M	Russia	"
L9 Barmine	UK	Blast resistant, pressure operated AT blast mine.
VS 1.6	Italy	"
VS 2.2	Italy	"
Type 72	China	"
M118 "Rockeye"	USA	Piezo fuzed, dual purpose submunition with shaped charge and fragmentation.
Mk. 82	USA	500 lb. high explosive air dropped bomb.
Projectiles, Grenades and Mortar Bombs		Various High explosive with side walls 0.25" - 0.5" thick

TABLE 1: PARTIAL LIST OF MINES AND ORDNANCE SUCCESSFULLY NEUTRALIZED USING LEXFOAM.

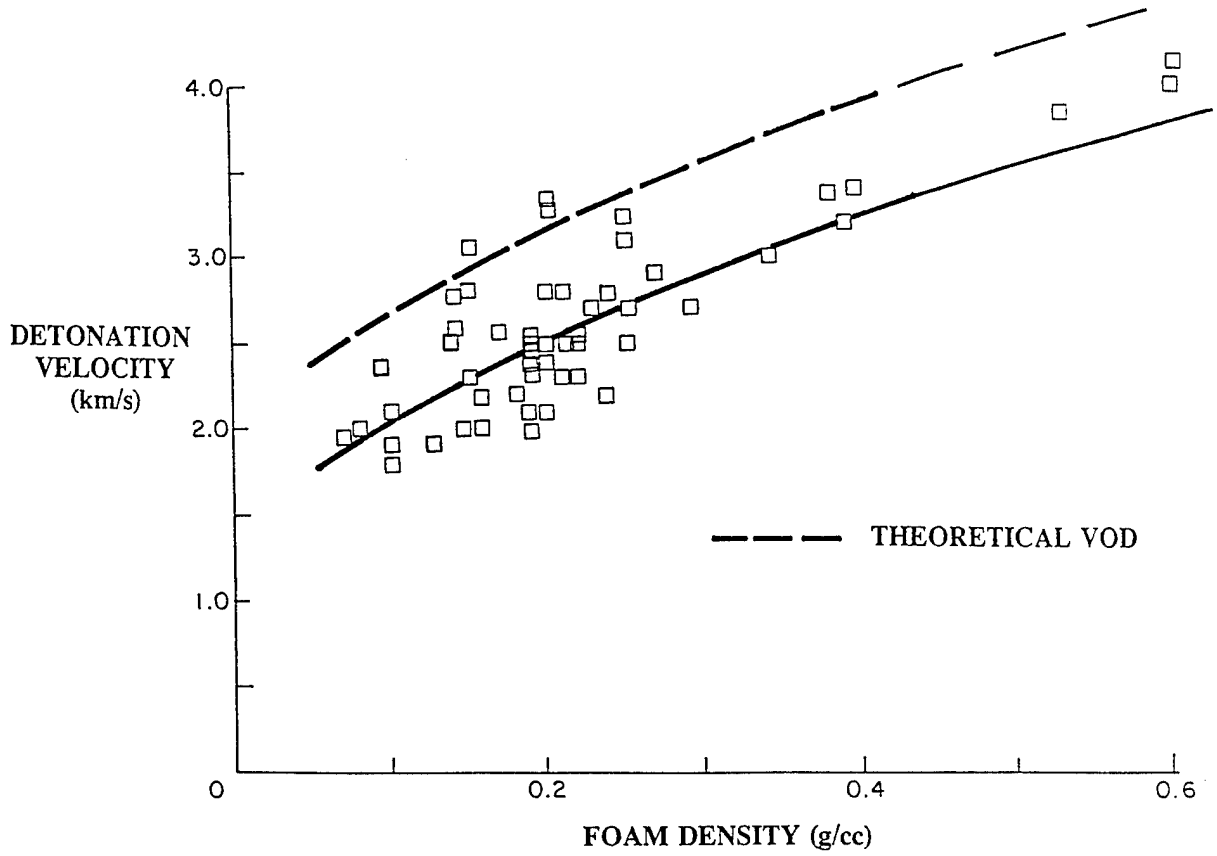


FIGURE 1: LEXFOAM DETONATION VELOCITY AS A FUNCTION OF FOAM DENSITY.

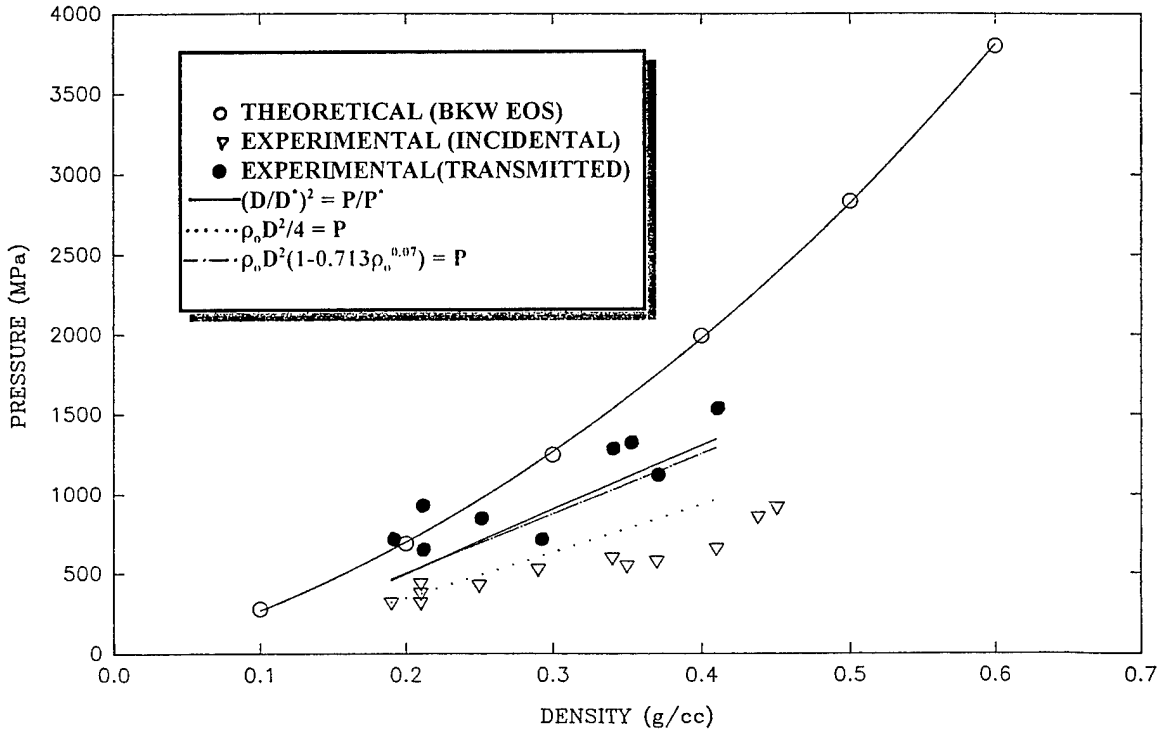


FIGURE 2: INCIDENT, TRANSMITTED AND CALCULATED LEXFOAM DETONATION PRESSURES AS A FUNCTION OF FOAM DENSITY.

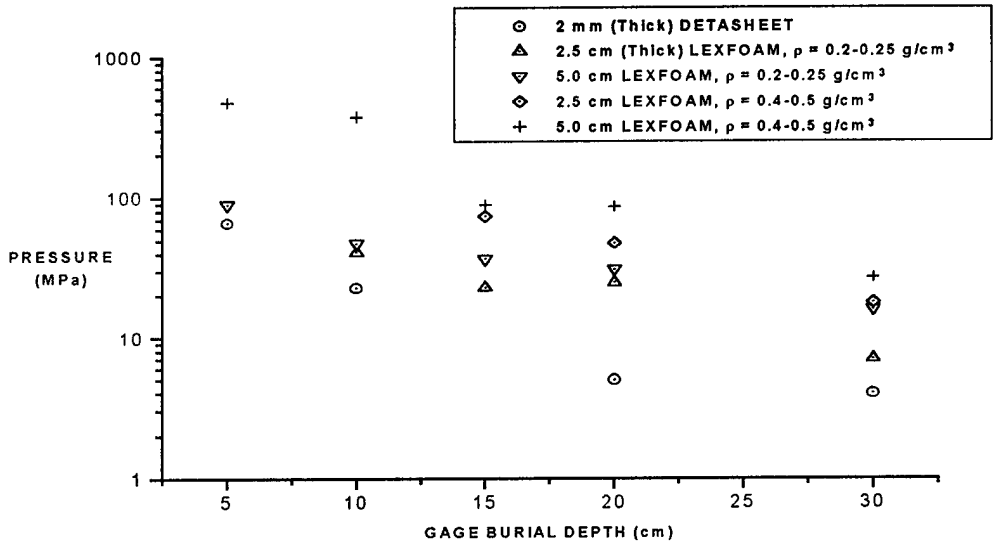


FIGURE 3: IN-GROUND PRESSURES AS A FUNCTION OF BURIAL DEPTH FOR VARIOUS LEXFOAM CONFIGURATIONS.

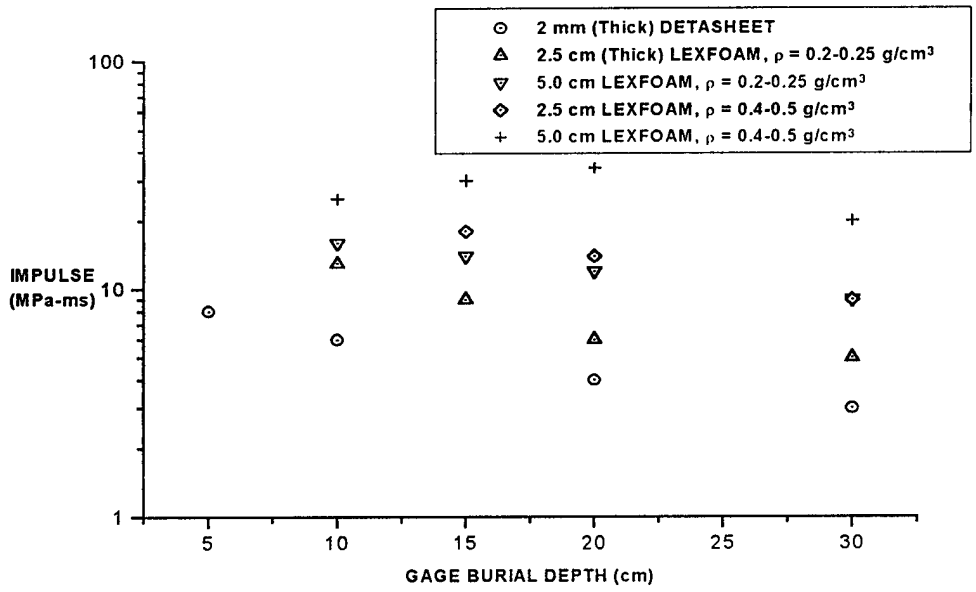


FIGURE 4: IN-GROUND IMPULSES AS A FUNCTION OF BURIAL DEPTH FOR VARIOUS LEXFOAM CONFIGURATIONS.

(5A) (5B)

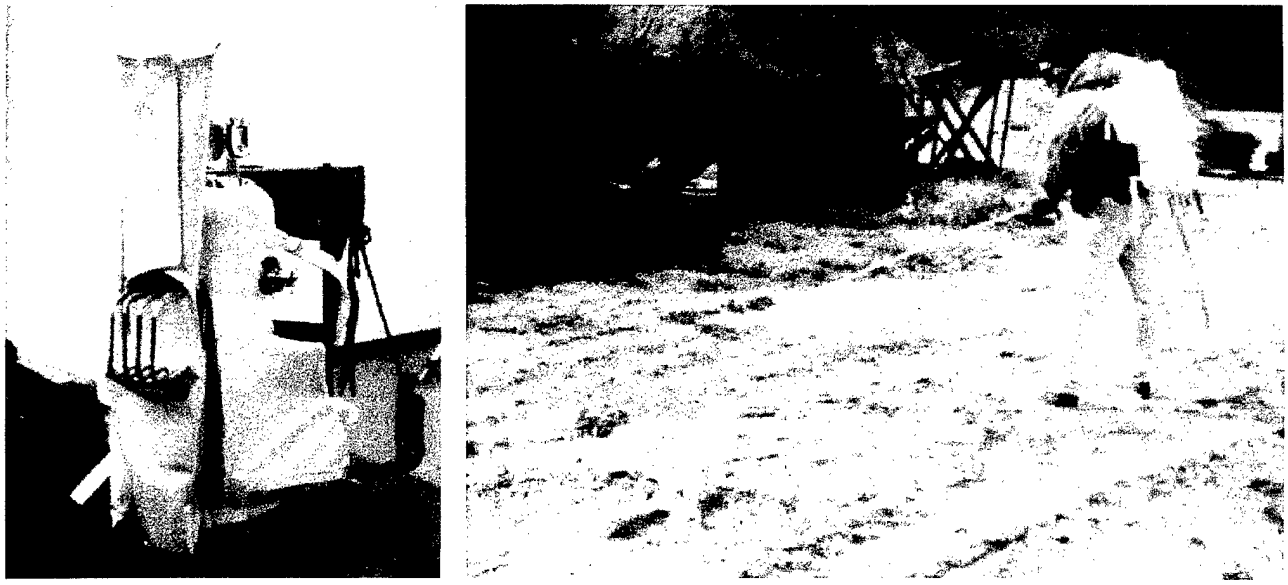


FIGURE 5: PHOTOGRAPHS OF BACKPACK DELIVERY SYSTEM COMPONENTS (5A) AND FULLY ASSEMBLED BACKPACK (5B).

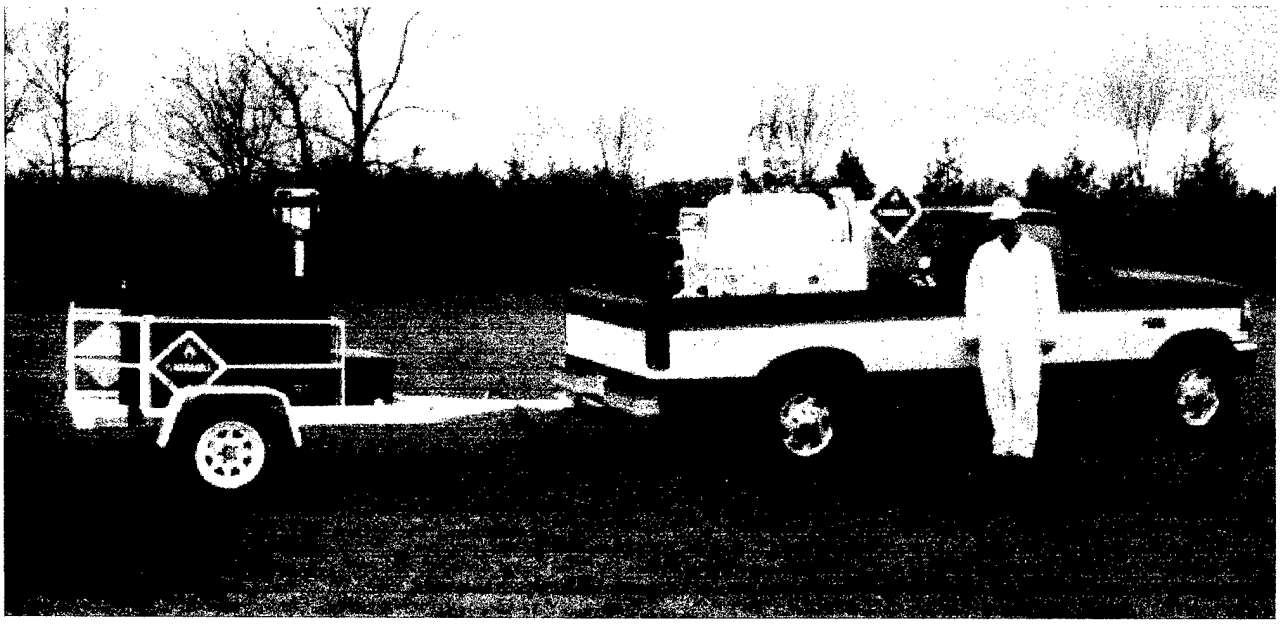
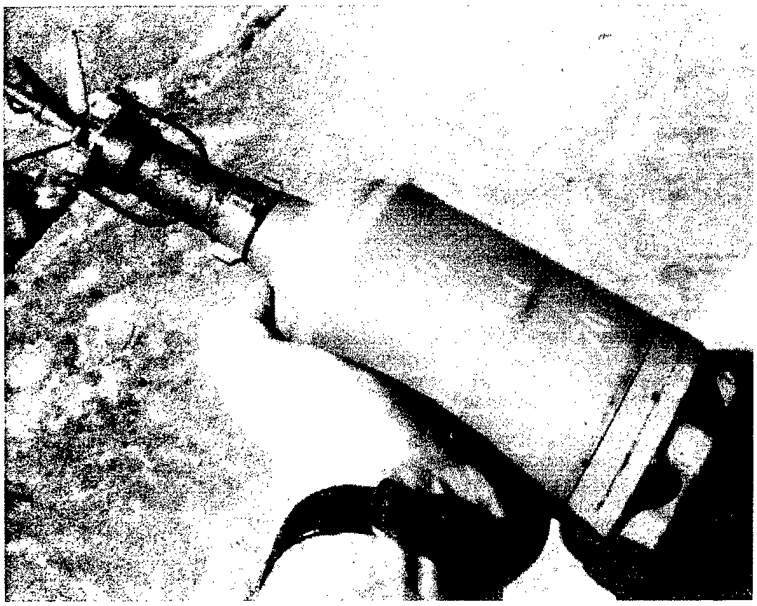


FIGURE 6: PHOTOGRAPH OF PALLETIZED DELIVERY SYSTEM, INCLUDING TRAILER AND THREE MOUNTED BACKPACKS.

(7A)



(7B)



(7C)



FIGURE 7: PHOTOGRAPHS OF THE PROM-1 BOUNDING FRAGMENTATION MINE (7A), PLACEMENT OF A DEMOLITION BLOCK (7B) AND LEXFOAM (7C) FOR MINE NEUTRALIZATION.

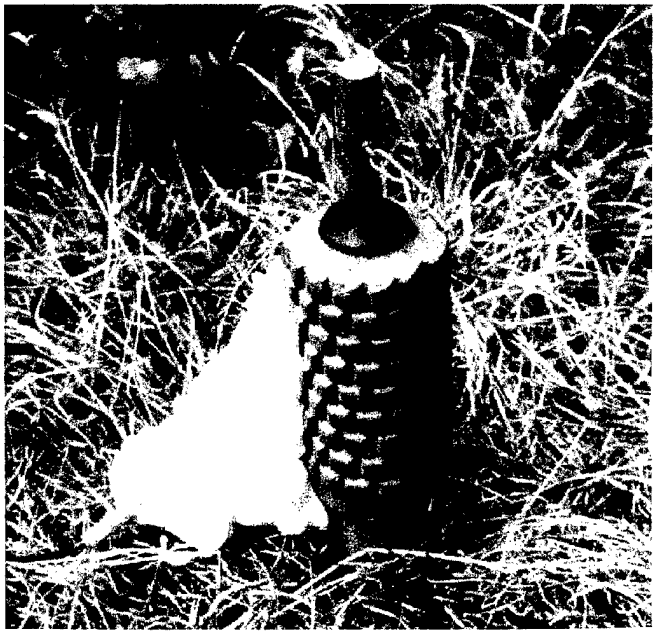
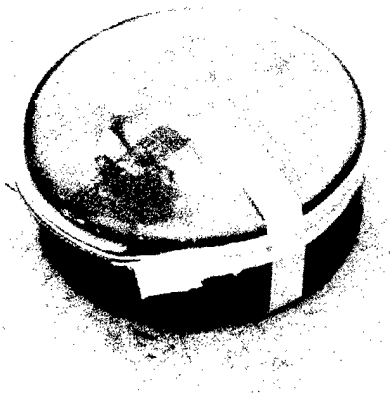


FIGURE 8: PHOTOGRAPH OF THE PMR-2A FRAGMENTATION STAKE MINE AND LEXFOAM CONFIGURATION FOR MINE NEUTRALIZATION.

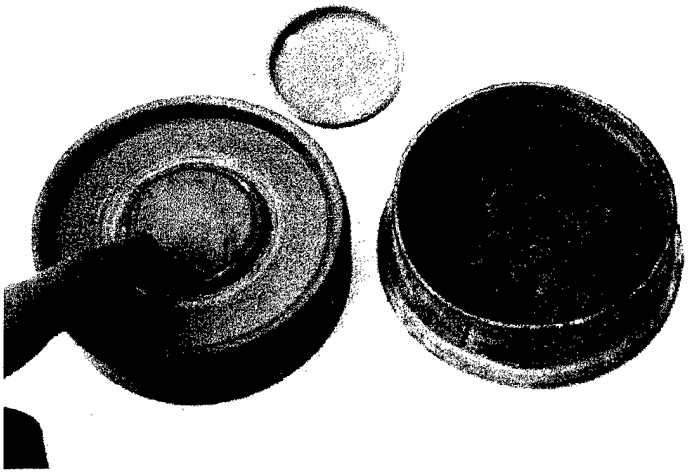


FIGURE 9: PHOTOGRAPH OF A CLAYMORE TYPE DIRECTIONAL FRAGMENTATION MINE AND LEXFOAM CONFIGURATION FOR MINE NEUTRALIZATION.

(10A)



(10B)



(10C)



FIGURE 10: PHOTOGRAPHS OF THE PMA-3 PRESSURE OPERATED BLAST MINE (10A), SHOWING THE PROTECTED EXPLOSIVE CAVITY (10B) AND DISPERSED LEXFOAM FOR MINE NEUTRALIZATION (10C).



FIGURE 11: PHOTOGRAPH OF A TYPICAL LEXFOAM CONFIGURATION UTILIZED FOR NEUTRALIZATION OF MINE CLUSTERS.

CHAPTER 5: PROGRESS IN AUTONOMOUS SYSTEMS FOR MINE WARFARE

AUTONOMOUS VEHICLES

The genesis for this series of Symposia on Technology and the Mine Problem is the vision that advances in the technologies of autonomous vehicles, sensors, power packs, navigation and control, and "work packages" will lead to a revolution in how mine countermeasures/countermine operations are carried out. It is toward the realization of this vision that we stated the objective of the Symposium was to "change the world". We at the Naval Postgraduate School firmly believe that the requisite technologies are nearly within grasp -- a view shared with us by the late Chief of Naval Operations, Admiral Jeremy K. "Mike" Boorda, USN.

Accomplishment of this vision will require continuity of effort. The goal is in sight. However, much remains to be done in proof of concept and operational demonstration. If one imagines a time line stretching from today's Navy on into the future, these revolutionary approaches will probably impact squarely on the "Navy after next". Mike Boorda was the kind of naval visionary who was comfortable with the idea of planning for the Navy after next even as he fought the budget wars to maintain today's force structure.

Those of us who believe in the ultimate promise of autonomous technologies received additional encouragement from the address by Major General Clair Gill, USA, Commanding General of the Engineer Center at Fort Leonard Wood, Missouri (see Chapter 2). In effect, General Gill said that the U.S. Army was taking up the challenge to field autonomous systems. Readers may recall that the challenge to the First Symposium in April 1995 was to develop a family or families of autonomous vehicles capable of carrying out some or all of the tasks of mine countermeasures at sea or countermine on land. These systems must be affordable, with unit costs on the order of $5,000 in production quantities of 100,000.

In this Chapter we have assembled papers that provide a report on the progress toward meeting this challenge. However, to use a metaphor from athletics, the address by Major Colin King, RA (Ret), editor of Jane's new volume on landmines (see Chapter 3), the bar has been raised. Major King drove home the point that the environments for land countermine operations are difficult. Few of the vehicular approaches now under development will be able to operate in most of these land environments.

At sea much the same has happened. ARPA and the Draper Laboratories have successfully demonstrated the capability to carry out extended mine reconnaissance through water of complex structure, but development of shallow water and very shallow water autonomous capabilities has been delayed by budget cuts. (Reference here is to ONR's Autonomous Ocean Network.)

The quest for truly autonomous mine countermeasures capabilities is entering a crucial stage. Funds for development and demonstration of components and subsystems that cannot be fielded for another five to ten years are short. These same resources are claimed by others with more immediate delivery dates. It is therefore essential that those individuals who serve in various advisory capacities to both the Army and Navy remain aware of the state of development and potential of autonomous systems. Unfortunately, these technologies are new and, in many cases, unfamiliar to many experienced scientific and operational individuals.

It is entirely possible that the more benign operational environments that one encounters in Humanitarian Demining operations will provide the first opportunities to distance humans from mine removal activity.

The 1998 Symposium on Technology and the Mine Problem will once again present sessions that provide status reports on progress toward obtaining autonomous systems for land countermine and sea mine countermeasures.

The Basic UXO Gathering System (BUGS) Program for Unexploded Ordnance Clearance and Minefield Countermeasures, an Overview and Update

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ABSTRACT:

The Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) is conducting an exploratory development program for the development of small, inexpensive, robotic technologies that enable systems that will clear unexploded submunitions and mines. Government, academia, and industry are working together to develop these technologies. The system that will use these technologies is called the Basic UXO Gathering System (BUGS), which consists of a reconnaissance platform that will provide identification and location of targets, and a number of small, inexpensive BUG (Basic UXO Gatherer) robots to perform Pick-Up-Carry-Away (PUCA) or Blow-In-Place (BIP) operations. Different concepts for the individual BUG vehicles are being developed and tested in the field. An autonomous reconnaissance platform, based on an existing EOD robot, is being developed for UXO target identification and location. An anti-mine munition is being explored for placement on mines by the BUGs for mine neutralization. Modeling and simulations are being used to predict how multiple robot systems would perform the desired missions, prior to building a small fleet of these BUGs.

INTRODUCTION:

The task of removing UneXploded Ordnance (UXO) by Explosive Ordnance Disposal (EOD) technicians puts these personnel under great risk. The risks are associated with the new technologies used in the submunitions or mines, such as anti-tamper features, and the factors that these objects have been subject to weather and environmental conditions that could trigger detonation at any time. However, military operations require that UXOs and mines be cleared from strategic areas. Also, practice ranges and other lands that are contaminated by ordnance or mines must be cleared so they can be converted back to more beneficial use. Not only is the cost of training personnel in locating, gathering or disposing the unexploded ordnance enormous but this activity puts the EOD technician in great physical danger.

The main force behind building most robotics systems is to reduce the human presence in dangerous task areas such as UXO clearance and de-mining. The difficulties of performing complex tasks in the real world environment present a challenge for engineers in designing a fully autonomous system. Furthermore, the cost of building a single intelligent robot fully equipped with complex sensor capabilities is too high for use in UXO gathering or mine detection because of the risk associated with equipment destruction. The NAVEODTECHDIV goal is to develop a low cost, easy to use, and simple to maintain system to perform the Explosive Ordnance Disposal (EOD) mission. The BUGS concept consist of a reconnaissance platform with suitable sensors to detect and locate the submunition from a safe distance, and then using a low cost, simple Basic UXO Gatherer (BUG) to perform the Pick Up and Carry Away (PUCA) or Blow In Place (BIP) function. Once the desirable behavior of a single simple robot is obtained, the same architecture then can be distributed to all other similar platforms to create a group of robots to accomplish a practical and vital mission. It is believed the BUGS system of cheap, simple robots, operating collectively to accomplish a mission, will be faster, cheaper, and easier to build then a single high cost intelligent robot.

EOD / MCM MISSIONS:

The primary mission considered for the BUGS system is the clearance of scatterable submunitions. The goal is to have a system which can gather a large number of unexploded submunitions to one location that can be disposed of at one time. This is the Pick Up Carry Away (PUCA) procedure that is currently employed in some cases by EOD technicians. The act of disposing (with an explosive charge) a stockpile of UXO items is much quicker than disposing of numerous individual items that are spread out over a large area. The EOD technician will be safer since he will not have to traverse an area littered with UXO to place numerous individual charges, and will not have to handle the UXO's himself. Proximity sensors, tripwires, and the like are being used more frequently in submunitions, making the EOD technicians task more hazardous. Also, submunitions are so cheap to manufacture, large numbers are used at one time, and the low cost is indicative of low reliability, leading to many duds that must be cleared. The small gatherer robots of the BUGS system will perform the most hazardous tasks.

Another important mission that is considered for BUGS is mine countermeasures. For breaching a minefield, the practice of deploying large nets filled with explosives works well, but is not efficient nor does it take advantage of the knowledge of the location of individual mines. This knowledge of locations is being developed by several mine detection technology projects currently underway. The individual BUG vehicles can covertly place neutralization charges over mine targets, and at the appropriate time, a single command from a remote operator can initiate the charges, rendering safe a required portion of a minefield.

SYSTEM CONCEPT / TECHNICAL APPROACH:

The BUGS system concept consists of a three phased approach. The first phase is to detect and locate targets to be collected or neutralized. The second phase consists of either reacquiring and gathering the targets, or placing neutralization charges on the targets. The final phase consists of actually neutralizing the targets. The approach of using these three phases, using different assets, will accomplish the desired missions.

The detect and locate target phase is first. A sophisticated sensor platform can be used to perform this task, such as the USMC's COBRA or the Army's ASTAMIDS landmine detection and location systems that are being developed. For targets that are not buried, such as submunitions in the UXO scenarios, a human can perform this task. He can visually detect the targets and record locations with a GPS receiver, or some other local positioning system. NAVEODTECHDIV has recently developed the Remote Controlled Reconnaissance Monitor (RECORM), which is a teleoperated robot with a camera used by an EOD technician to remotely survey a hazardous area for ordnance targets. For the UXO scenarios, RECORM is being automated to autonomously perform an extensive area search, recognize targets optically, and record the target locations.

The second phase is the reacquiring and collecting targets, or placing neutralization charges on the targets. For the UXO mission, the approach is to gather the small submunition targets in a central location. This collection of UXO's can then be neutralized at one time, providing a savings of time and explosives for the EOD technician as opposed to neutralizing each of numerous targets individually. For the MCM mission, the approach is to place an anti-mine munition over each mine target for later simultaneous detonation. The individual BUGs will be loaded with target location information gathered in the first phase. They will then go to the proximity of the targets, individually, and reacquire the targets using low cost sensors. These low cost sensors are being developed under a number of other programs, and the technologies being developed will be inserted into this program. The vehicles to perform the gathering function or placing munition function have to be autonomous and cheap. They must be autonomous to allow the use of numerous vehicles by one operator, to realize time efficiencies. They must be cheap so that numerous vehicles can be afforded, and a few can be replaced in the event that one may be inadvertantly be destroyed. Small vehicles operating in an area littered with UXO's or mines, and handling explosives, have some

probability of being destroyed.

The final phase is the neutralization of the targets. For the UXO mission, this would typically consist of an EOD technician placing an explosive charge on the collection of submunitions, and neutralizing the collection at one time. For the MCM mission, with the anti-mine munitions in place over the mine targets, a command from a standard military transmitter, such as the MK186, can simultaneously initiate the munitions to neutralize all of the mines. A study has been completed by Naval Surface Warfare Center, Indian Head Division, that shows the feasibility of using a semiconductor bridge initiator on a scaled-up version of an existing anti-mine munition can meet simultanaety of initiation and neutraliztion requirements.

PROGRAM APPROACH:

The program approach taken for this project is to concentrate on technologies that will enable different system concepts to be demonstrated, with a strong emphasis on control system technology. For the small, autonomous gatherers, several contracts were awarded so a variety of concepts could be demonstrated and evaluated. In addition to these contracts, NAVEODTECHDIV developed its own system concept in-house. Each of these concepts are being modeled by the Naval Postgraduate School based on inputs from the developers and observed performance. These system models are being run against various UXO clearing and minefield neutralization scenarios. Each of the concepts developed is being tested at NAVEODTECHDIV against a test plan designed to exercise the control subsystems. This testing is further described later. Information about general technology areas are provided by government agencies to each of the developers to reduce the burden on them, and allow them to concentrate on the control systems. The Naval Postgraduate School is providing modeling and simulation assistance, NAVEODTECHDIV is providing information about sensors and detectors, and NCCOSC is providing information about navigation and control systems. A technical system concept study, the test results, and the results of the modeling will be used together to determine which concept will be pursued in the next phase of the project, which is a multiple vehicle system demonstration.

For the target detection and location platform, we contracted with Lockheed to develop a package to be integrated into the EOD RECORM vehicle for autonomous detection, location, and indentification of UXO targets using visual means. The Robotic Work Packages developed for NAVEODTECHDIV for autonomous survey of underwater ordnanace items is being adapted for terrestial use on RECORM. This vehicle will work with the gatherers to demonstrate the feasibility of our system concept.

GATHERER CONCEPTS:

For the individual gatherer vehicles, several industry contractors have been developing initial concept robots. For this initial phase of the project, the emphasis is on the control system that will lead to expansion into a successful multiple vehicle system. A demonstration of these competing single robot approaches to UXO clearance and/or minefield neutralization was performed in July at NAVEODTECHDIV. The gatherer vehicle control system concept developers include Foster-Miller, ISX / IS Robotics, Draper Laboratory, K^2T, and NAVEODTECHDIV.

Foster-Miller: Foster-Miller is using a vehicle similar to their Lemmings, which is a battery powered, tracked vehicle capable of traversing a wide variety of terrain. It is symmetrical, and is designed to flip over and continue traveling if necessary. It is taller than the Lemmings, since an array of antennae is located on the top and bottom for receiving homing signals. For the initial concept, beacons will be placed on the targets to guide this vehicle. Beacons may also be used to identify waypoints. Radio frequency transmitted from the beacon is used for the vehicle's homing from long distances in to approximately six feet. The vehicle recalculates the desired angle of travel, and turns to this angle, every six to ten seconds. Closer than

six feet, an array of light emitting diodes on the beacon is used for homing directly, without any time delay in changing direction. A magnet is used to pick-up the metallic targets and carry the anti-mine munition.

The Foster-Miller control strategy is quite simple. It is designed to operate in an unstructured environment, and maximizes the mobility potential of the vehicle. Sensors are not used to detect obstacles, and the vehicle is expected to traverse obstacles, or if it gets stuck, it will back up and turn, and continue traveling. If the vehicle flips over, this is acceptable, since the vehicle concept is to operate even if it is upside down, like the Lemmings vehicle. The vehicle's goal is to reach a beacon. A heading towards the beacon is recalculated every six to ten seconds, and the vehicle makes a turn to that heading and continues forward. In the final configuration, once the beacon is reached, the vehicle will either perform a pick-up function or a drop/place function, depending on the beacon and the mission (either PUCA or BIP). The vehicle would then know which beacon should be approached next. The beacon homing navigation scheme could be replaced in the future with some other type of navigation / location system.

ISX / IS Robotics: IS Robotics is using a variant of their Pebbles III vehicle, which is a small, battery powered, tracked vehicle. A DGPS system is used for location and navigation information. An operator control unit, being developed by ISX, is used to interact with the vehicle. This control unit will serve as a central data collection for the vehicle, a vehicle activity coordinator, and a control interface between vehicle and the operator. A mission for the gatherer vehicle is communicated from the control unit to the vehicle. A joystick at the control unit can be used to tele-operate the vehicle when needed, and a series of "go to" commands can be entered for the vehicle to communicate the target locations. An electro-magnet mounted to an arm is used for a manipulator.

The ISX / IS Robotics control strategy is a supervised autonomy, dependent on sensor inputs. Infrared sensors are used to detect obstacles, bumpers detect collisions, and inclinometers measure the slope and roughness of terrain. The individual robots are programmed with a behavior control paradigm. Behavior control facilitates rapid reaction to environmental hazards and robust response to system failures. Multiple independent behaviors compute commands for the robot's actuators, based on sensor inputs, and an arbitration module resolves conflicts. The robots monitor their own progress and alert an operator if there is an anomaly. As mentioned above, the operator control unit will serve as a central data collection for the vehicle, a vehicle activity coordinator, and a control interface between vehicle and the operator. Constant communication is required between the individual robot and the control unit, transmitting location and status information. A map is maintained of detected obstacles, clear areas, and targets. Constant communication is also required between the robot and the DGPS base station for precise navigation. Dead reckoning is used as a secondary navigation system, and can be used exclusively, though with decreased accuracy, if the DGPS system is unavailable or inoperable.

Ultimately, the operator control unit will plan paths for the robots, based on known obstacles, or locations of obstacles as they become known by other robots in the field and mapped. If an individual robot gets itself stuck, and calls for help from the operator, the operator can tele-operate the robot with a joystick, watching a video display from a camera mounted on the robot.

Draper Laboratory: Draper Laboratory is using an evolution of their MITy-series of vehicles, which is a 6-wheel drive flexible frame micro-rover driven by battery powered motors. Draper's local positioning system is an optical-electrical one, with two tripod-mounted beacons that emit a rotating laser beam. Dead-reckoning is used as a backup navigation and positioning system. Draper also employs an operator station which serves as an automated mission management host. A wide scoop on the front of the vehicle is used for a manipulator.

The hierarchial control strategy for the Draper Lab concept is dependent on sensor inputs, too. Sensors are used to detect obstacles and collect information about the world. This requires constant communication of sensor data and vehicle location with a operator station to create a map. The vehicle has two speeds. In the slow mode, it is collecting information from the sensors, which are fully active, and the

operator station is creating a map, melding the sensor information with any other map information that may be known a priori. In the fast mode, the vehicle is traveling along paths that have been identified by the operator station as being clear of obstacles. The three critical activities of the operator station are mission management and mission planning, maintenance of target and path maps, and human operator intervention as needed. The operator station performs autonomous mission management and mission planning, and sends four types of commands to the individual vehicles; waypoint-slow, waypoint-fast, collect UXO, and deposit UXO. The waypoint-slow command is issued to a vehicle to proceed to a commanded location while detecting and avoiding obstacles and hazards. The waypoint-fast command is issued to proceed to a commanded location, but a clear corridor is known to exist between the current position of the vehicle and the waypoint. The collect UXO command is issued when a vehicle locally detects a UXO, and the deposit UXO command is issued when a vehicle, with a UXO onboard, reports that it has reached the ordnance disposal area. The collect UXO and deposit UXO functions can be aided, if required, by an operator using a camera onboard the vehicle. Five kinds of data are transmitted from the individual vehicles to the operator station. These are the announcement of completion of the current command, announcement of failure of current command, regular updates of vehicle position, location of detected UXOs, and location of detected obstacles/hazards.

The autonomous planning performed by the operator station consists of hierarchical planning, route planning, and road-building. The hierarchical planning decomposes tasks in steps, or levels. At each level, a set of tasks is decomposed into subtasks. The top level controller deals with mission goals, the middle level deals with subgoals derived from the mission goals, and the low level deals with commands to the vehicle. However, the Draper's planning does more than simply break down big jobs into little ones. At each level of planning hierarchy, the value of accomplishing tasks is traded off against the cost of consuming resources. An initial plan is repeatedly modified using heuristics in an attempt to generate a plan of maximum expected utility. This simulation procedure is an iterative improvement scheme wherein, for each iteration cycle, the heuristic search attempts to improve on the current solution. The steps of the mission planning cycle are repeated over and over, until the time allotted to the planner for planning has been exhausted, or a point of diminishing returns has been reached. Each level of the planning monitors the performance of the plan and compares it to the performance expected when the plan was created to determine the plan's fitness. When the value of the plan being executed falls below its potential value, the planning process begins anew, and uses the results to modify the plan during execution. An outcome of this process is the identification of "roads", which are used over and over again as the vehicles traverse the field, gathering UXO targets or placing anti-mine munitions.

K^2T: K^2T has designing a new legged, walking vehicle that is being investigated for the BUGS program. This vehicle has eight legs, and is biologically inspired, applying concepts found in the mechanisms of locomotion, manipulation, and neural control in biological creatures. K^2T has teamed with Case Western Reserve University for the control system. The first vehicle has just been built, and is now becoming operational. This concept is of particular interest for situations where difficult terrains are encountered. Walking vehicles are expected to have much better mobility than wheeled or tracked vehicles.

NAVEODTECHDIV: NAVEODTECHDIV designed and built a new vehicle for this program. It is a small, battery powered, wheeled vehicle, and uses a DGPS system for navigation, with dead reckoning as a backup system. As an autonomous system, it does not employ an operator's control station.

The control methodology for this concept is a layered subsumption approach. There are three levels of controllers used. The highest level controller maintains the overall mission goals, and receives and sends data externally, such as DGPS data and remote operator commands, such as initial mission goals, including target locations. The lowest level contains the subsumptive control modules in the sensor controller that generate behaviors in response to real-time sensor inputs, and a motion controller that controls the motors on the vehicle. The middle level controller acts primarily as a data handler, channeling data between the other

controllers. Since the vehicle's response is based on various asynchronous external stimuli, such as navigation, communication, or environmental data, specific modular programs can operate on each stimulus or command independently. In this way, each specific modular function of the robot is capable of reacting to the unknown terrain real-time. Likewise, the specific coordination of the overall behavior is still performed by its central coordinator to achieve this objective. The centralized coordinator is flexible and does not control the robot's actuators directly or manage tracking and navigating by itself. Instead, the coordinator provides indirect control by selecting among alternate functional modules. Therefore, a combination of simple subsumptive modules with some hierarchical central control to prioritize its decisions is used to achieve the vehicle's mission objective.

TESTING OF GATHERER CONCEPTS:

A test plan was written to exercise the various control systems for the different gatherer concepts. To carry out the testing, a test field was established at NAVEODTECHDIV. The test plan includes individual tests of local search routines, that are required to reacquire targets, obstacle avoidance and maneuvering routines, and signal loss tests. Each of these tests were designed to gather information on how the control systems perform. The obstacle avoidance and maneuvering tests include a long, straight obstacle, an "L" shaped obstacle, and a blind alley. The gatherers must approach these obstacles from different angles and find a target on the opposite side. For the blind alley, the gatherer must find its way into the alley, find the target, and find its way back out of the alley. The signal loss tests include the loss of GPS data from the satellites and the loss of radio frequency communications.

In addition to the individual tests, there are two multiple target "field tests". For the UXO field test, UXO targets are placed at many locations within a 100 foot by 100 foot test area, behind various obstacles and on several different types of terrain, such a sand pile and a pile of rocks. The test is to have the vehicle autonomously attempt to find as many of the targets as possible, picking up and carrying one at a time, and depositing them in a central disposal area. For the mine countermeasures field test, the vehicle is to autonomously deliver a simulated anti-mine munition to each of four landmines that have been buried to be flush with the surface of the ground. All targets used are metallic for some level of ease of detection.

Three other tests, included in the test plan, were designed to gather information on some particular feature of the test beds, but not the control systems. These include the ability of the manipulator to pick up an inert M42 grenade, used as our standard UXO target. Also, the ability of the manipulator to release the UXO was tested, along with its ability to place the inert anti-mine munition. And the other test was a simple straight line transit test to see how well the vehicle could travel to a point some specified distance away, with no obstacles.

From the testing performed to date, we have been able to make the following observations. The Draper Lab system has a very good control station, a very fast vehicle, and can perform waypoint navigation. The NAVEODTECHDIV vehicle has been able to successfully perform local searches and manipulator operations. The Foster-Miller vehicle has good terrain mobility, and can home to a beacon very well, even though the radio frequency communication is very close to the ground and the antennae array spacing is tight. ISX / IS Robotics has a good operator control unit (on a laptop computer), and the vehicle can perform the different functions autonomously, in an integrated fashion. Much of the value of these tests, though, will be that they provide real world inputs to the computer modeling of the different proposed concepts.

MODELING / SIMULATION:

Simulation, obviously, is not a substitute for the real world. Only robots operating in the real world terrain can provide the reliable data and results. There are many different environments that the simulation cannot be characterized exactly or accurately. Likewise, it is difficult to build a "standard" simulation to compare the performance of different system approaches to the same application. All BUG concepts are attempting to solve the same problems; however, their system approach, response, complexity or trade-offs are different. It

requires extensive work for the programmer to integrate 4 or 5 different packages of simulation into one system. On the other hand, while real world testing is always better, it is time consuming and expensive.

Direct ground testing requires time and experience of the developers to tell where the optimal tradeoff point is. Depending on its tasks, real robots can damage themselves, their surroundings, other equipment or possibly people. Real robots often malfunction due to temperature change, break down mechanically or electrically, or exhaust their battery power. From this perspective, especially for hazardous missions or big projects, simulation is important both for safety and financial reasons. In the case of BUGS, simulation is used as a rapid prototype statistical analysis tool and a demonstration tool.

The Naval Postgraduate School is building a simulation that includes a world scale model of the Marine Corps Air Ground Combat Center, Twenty Nine Palms terrain and a variety of robots that have the "same" functionality or characteristics as a real robot. Since the study of agent group behaviors is an emerging field, this simulation is a useful tool for studying the interaction and cooperation between a large number of agents in the real world. This simulation will solve the difficulties of implementing actual real world testing or analyzing a large number of agents in a complex world. In addition, the simulation provides the developer with a general understanding of the total system characteristics through a large number of simulations of diverse situations. The repeatability of the simulation can provide the designer with insight into the interaction of the agent's behaviors and its environment and provides the operator with historical data records on each simulation for further analysis. The simulation will be used during the entire life of the project, to support continuous changes and to validate ideas for future improvement in a safe environment. This will simplify the developers' tasks in term of time, space, accessibility and costs over the long run.

Both UXO clearance and mine countermeasures scenarios have been modeled, as well as the various gatherer vehicle concepts. Variations of sensor capabilities, navigational accuracies, number of vehicles working in unison, and the like are being explored through running the model many times. The results of this modeling will assist in the evaluation of different control strategies.

PLANNED WORK:

The planned work for the BUGS project for FY97 includes completion of the testing of the initial individual gatherer vehicles, and completion of the computer modeling and simulation by the end of November. Based on the test results, modeling results, and system concept study reports, a concept will be selected to advance to the development of a multiple vehicle system. This multiple vehicle system will be demonstrated, showing the utility of using numerous small robots to perform UXO clearance or minefield neutralization missions. For the sensor platform for the UXO missions, work will continue on the development of the autonomous RECORM vehicle, to autonomously search an area, detect and classify targets, and provide target locations to the small gatherers.

SUMMARY:

The BUGS program is proceeding along as planned. Different control system concepts for the individual BUG vehicles have been developed, demonstrated, and are being evaluated. They are being evaluated as a single vehicle concept in actual hardware testing at a test site, and as a multiple vehicle concept in computer modeling and simulation. The real life testing is being used to develop the computer modeling. Demonstration of a selected multiple vehicle concept will follow next.

In addition, an initial autonomous survey platform for visible UXOs is being developed, using an EOD robotic asset, and adapting the Robotic Work Packages that have been developed for autonomous underwater EOD use.

The BUGS system vision of cheap, autonomous, simple robots, operating collectively to perform a hazardous, but important mission, is proving to be a viable idea.

Small Autonomous Robotic Technician

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Abstract

Clearing unexploded ordnance (UXO) is currently a dangerous and slow process that exposes personnel and equipment to considerable risk. Draper Laboratory is currently developing a system using affordable, small robotic vehicles to navigate to areas of indicated UXO, locate them, pick them up, and carry them away to an ordnance disposal area (ODA). For buried mines, a charge is to be placed. A remotely located operator monitors the robotic vehicles and supervises or directs activities when desired. The SMall Autonomous Robotic Technician (SMART) system is transported to a site and deployed by a single operator. This system allows a single operator to safely accomplish much of the work that now requires and risks many expert ordnance disposal personnel.

The SMART system includes: a 6-wheel drive flexible frame micro-rover called a BUG (Basic UXO Gatherer); control station with map building and path planning/re-planning capabilities; 2-DOF grappler assembly; and a local positioning system. Using the planning and mapping capabilities, the mission management system can carry out the UXO clearance mission by means of an efficient road-building approach. In this approach, the micro-rover uses high speed and low speed transit modes depending on the terrain obstacle information

1. Introduction

Clearing unexploded improved conventional land munitions is an important task that currently requires slow, expensive processes exposing personnel and equipment to considerable risk.

In the current manual UXO clearing approach, areas suspected of having UXO are first partitioned into sectors with corners delimited by flags. In each sector, a four- to eight-man sweep team (Figure 1) visually scans the area for UXO. Based on preliminary investigations, the risk during the manual sweep is considered much less than the risk involved in clearing the UXO. UXO are dangerous and can explode or detonate even if handled with care.

Once a UXO is located, all branches of the military, except the U.S. Marines, execute a blow-in-place (BIP) procedure: personnel place a detonation charge, stand off 1000 yards, and return 30 minutes after detonation. The Marines execute a manual pickup and carry-away (PUCA) procedure to gather the UXO in a common location for later detonation (Figure 2).

The role of the SMART system is to provide affordable, small robotics technology to clear UXO safely while reducing the number of personnel required.



Figure 1: Sweep team looking for UXO. Note the terrain and natural obstacles that present a challenge to robotic vehicles.



Figure 2: UXO gathered by the sweep team in a PUCA mission. Note the variation in size, shape, and appearance of each UXO.

2. Intelligent Unmanned Vehicle Center

The Intelligent Unmanned Vehicle Center (IUVC) was first established in August, 1990, as the Planetary Rover Baseline Experiment (PROBE) Laboratory. The laboratory represents a cooperation with the Charles Stark Draper Laboratory and area universities (MIT, Tufts, Boston University, Northeastern University) to actively foster research and design of intelligent systems including small robotic technologies. Currently, eight graduate and four undergraduate students from MIT comprise the student staff in the center.

Since the inception of the PROBE Laboratory, the center has developed a solid background in autonomous robotics and intelligent systems. The IUVC boasts, as its core competencies, the following specialty areas:

- Smart Sensor Technology
- Sensor Fusion
- Teleoperated Robots
- Autonomous Microrovers
- Autonomous Helicopter
- Undersea Mobility - "tuna" concept

Early small vehicle designs include the MITy-1 and MITy-2 (Figure 3) micro-rovers which are functional proof-of-concept prototypes for fieldable autonomous robots.

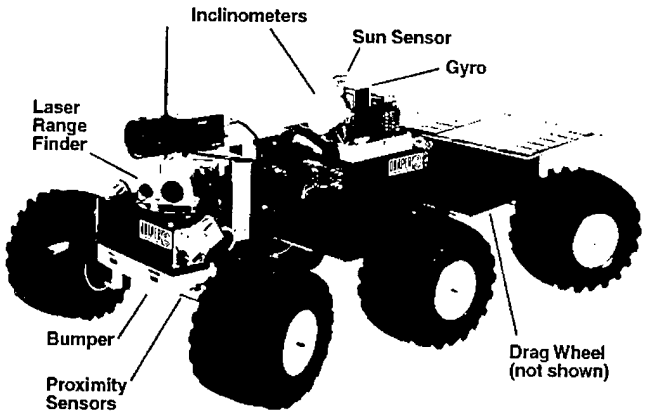


Figure 3: MITy-2 Micro-Rover

These MITy prototypes are the predecessors for the current SMART system vehicles, which we have labeled the EOD series. EOD stands for Explosive Ordnance Disposal.

3. System Description

3.1 Mechanical Design

Figure 4 shows the most recent configuration of the BUG known as EOD-2. The vehicle is equipped with a six-wheel drive flexible frame, front and rear Ackerman[1] steering mechanisms, a modular chassis, and a grappler mechanism for UXO retrieval.

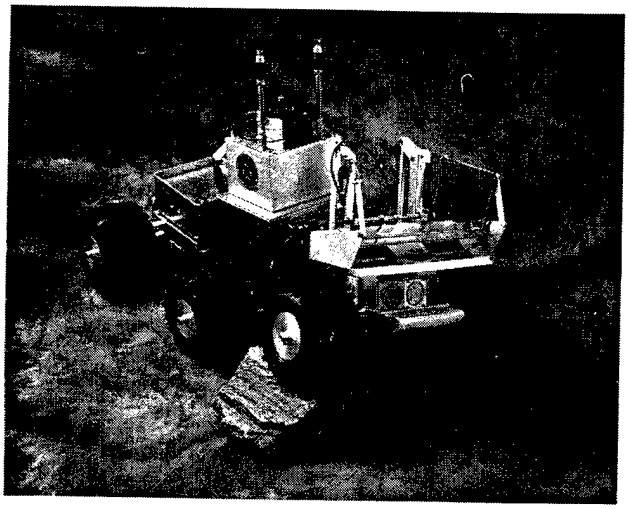


Figure 4: SMART System Vehicle, EOD-2

[1] This method of steering is based on a design that terminates the center point of each wheel at a common point. Using this design helps to reduce slippage during a turn and can therefore reduce navigation errors.

For parallel development purposes, the IUVC has developed a similar BUG, called EOD-1, (Figure 5) which shares the same basic mechanical architecture with EOD-2, but lacks a complete sensor suite and grappler mechanism. Table 1 presents a contrast and comparison of the various mechanical and electrical components for each vehicle.

3.1.1 Flexible Frame and Modular Chassis

The vehicle's flexible frame provides a high degree of maneuverability, enabling the rover to traverse rocks, curbs, and uneven terrain. The frame is constructed of three individual platforms

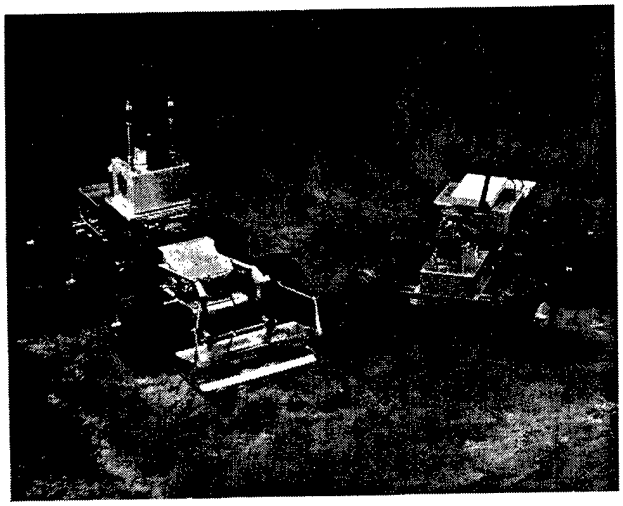


Figure 5: EOD-2 and EOD-1 SMART Vehicles

connected by flexible wire. The front platform contains a metal detecting unit, sonar electronics, a bumper, and the 2-DOF grappler mechanism. Housed in the middle platform is the onboard microprocessor, video camera and transmitter, serial modem, LPS transponder, and additional control circuitry. Finally, the rear platform contains power regulation circuitry and batteries. (See Figure 9 in section 3.2 for a schematic diagram showing the location of these components on the three chassis modules.)

Creating a highly modular chassis, this configuration allows the operator to swap individual platforms from other BUGs - a valuable option, given the potential for vehicle damage in the mission zone.

3.1.2 Drive Train

Six wheel drive also contributes to exceptional maneuverability, producing vehicle speeds up to 6 ft/s (1.8 m/s). Each aluminum wheel hub, fitted with a knobby rubber tire, is powered by a small (9.8 oz) 12V DC motor[2] with an integrated planetary gearhead and optical encoder. The optical encoders provide feedback used for autonomous navigation purposes.

3.1.3 Steering System

At the heart of the Ackerman steering system are two 24V DC motors[3], also equipped with integrated planetary gearheads and optical encoders. The gearhead output shafts are coupled to doubly threaded worm gears which are mounted in aluminum gear boxes (Figure 6) near the front and rear of the BUG. The worm gears mate with worm wheels inside the gear boxes, providing an overall steering ratio of 30:1. The mechanical linkages providing the Ackerman steering, combined with both front and rear "crab" steering yield a tight turning radius.

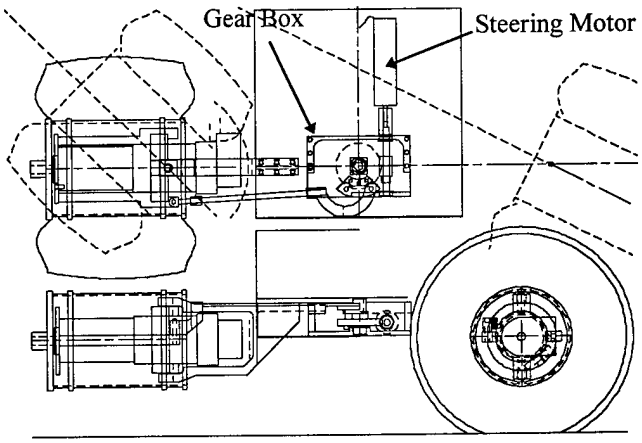


Figure 6: Schematic diagram of the Ackerman Steering mechanism.

3.1.4 Grappler Mechanism

The grappler mechanism (Figures 7 & 8), positioned on the front platform of EOD-2, serves a dual purpose. It is used to both detect and acquire UXO in a PUCA mission. Embedded in the base of the acrylic grappler bed is a metal detecting unit used during the execution of a search pattern task to detect UXO. Upon detecting the UXO, the grappler mechanism is used to scoop the UXO (Figure 7) into the BUG for transport to the ordnance disposal area.

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[2] MicroMo® DC MicroMotors Series 3557 motor, 32PG gearhead, and HE optical encoder

[3] MicroMo® Series 1724 motor, 16/7 gearhead, and HE optical encoder

The grappler is driven by two 24V DC motors[4] equipped with integrated gearheads and optical encoders. These encoders provide feedback to the control system necessary for autonomous PUCA missions. One of the 24V motors is used to actuate the scoop linkage, while the other is used to drive the rake. The rake is used to sweep the UXO into the scoop during the acquisition process.

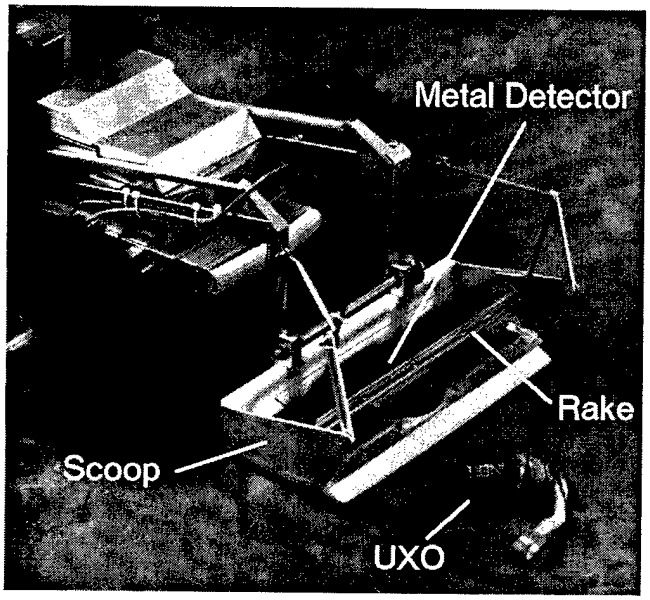


Figure 7: EOD-2 Grappler Mechanism

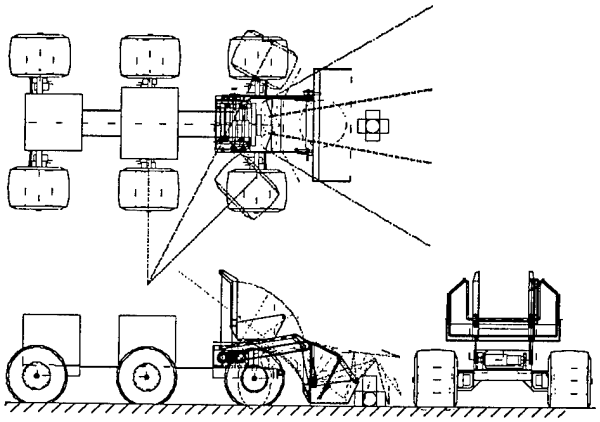


Figure 8: Schematic of the SMART system microrover

Table 1: Hardware Components for EOD-1 and EOD-2 BUGs

Component/ Capability	EOD-1	EOD-2
six-wheeled, three-platform mechanical architecture	yes	yes
six drive wheel motors with integrated encoders	on board	on board
scoop mechanism for retrieval of UXO	not available	on board
12MHz Z-World *Little Giant* Microprocessor w/ 512K SRAM & PI096 Digital Expansion Board	on board	on board
Systron Donner micro-mechanical gyroscope	not available*	on board
video camera & transmitter	on board	on board
front bump sensors	not available	on board
CONAC™ Local Positioning System (LPS)	not available	on board
Polaroid sonar ranging module array	not available*	on board
Proxim serial modem (9600bps)	on board	on board
Radio Shack metal detector unit	not available	on board

*Installation Planned

Table 2: Physical Specifications of the EOD Vehicles

Rover	Dim. (in)	Weight	Top Speed
EOD1	29 x 17 x 8	26 lb.	~ 6 ft/s
EOD2	29 x 17 x 16	36 lb.	~ 6 ft/s

3.2 Electrical Hardware

Figure 9 presents a schematic diagram of the basic electrical hardware layout of the SMART system EOD series microrovers. Sensors and various electrical hardware are distributed among the three chassis platforms, as discussed in section 3.1.

[4] MicroMo® Series 2338 motor, 30/1 gearhead, and HE optical encoder

3.2.1 Sensors

3.2.1.1 Sonar

Located at the front of the rover are three Polaroid sonar ranging modules. The ranging modules work by emitting a series of sound pulses and measuring the time elapsed until the echo returns to the transducer. The time measured can then be multiplied by the speed of sound at ambient conditions to calculate the distance to the nearest object.

The operation of the ranging module and the calculations for measuring the distance to the nearest object are handled locally by a Basic Stamp. This frees the main processor to perform other tasks while waiting for an echo return.

3.2.1.2 Bumper

Also located at the front of the rover is a bump sensor. The bump sensor is a small plate, spring mounted in front of two electrical switches such that depressing the plate causes the switches to close. The bumper signal is resistor tied high and the switch is tied to ground such that when the switch is depressed, the signal is pulled low.

3.2.1.3 Motor Encoders

Attached to each motor shaft is a rotary optical encoder. The encoders serve to measure the rotation of the motor shafts. The outputs of an encoder are two square waves that are 90° out of phase. This four-phase or quadrature output signal is then decoded by an HCTL 2016 quadrature decoder which tracks the angular position of the motor shaft with a 16-bit counter. Position is determined by multiplying the angular rotation of the drive motors by the wheel radius. Velocity is determined by measuring the rate of change of position.

Encoders are also used on the steering motors to determine the steering angle. When the power to the SMART rover is reset, the steering is centered using a pair of photodiode sensors. The steering encoders are then used to measure the rotation of the worm drive gear which is used to track the steering angle. The information from each motor is used in dead reckoning the SMART system navigation strategy.

3.2.1.4 Gyro

A micro-mechanical angular rate sensor is used to track changes in heading. A rate gyro offers much higher bandwidth than an electronic compass and is not affected by stray magnetic fields. The rate gyro outputs an analog voltage proportional to the rate of rotation. This analog voltage is low-pass-filtered to anti-alias the signal and digitized into a 12-bit digital signal. The digital signal is then locally integrated using a PIC16C84 microcontroller. The integrated signal is then scaled and returned to the main processor as the relative heading. The signal integration using a dedicated processor frees the main processor from the processor intensive task of numerical integration.

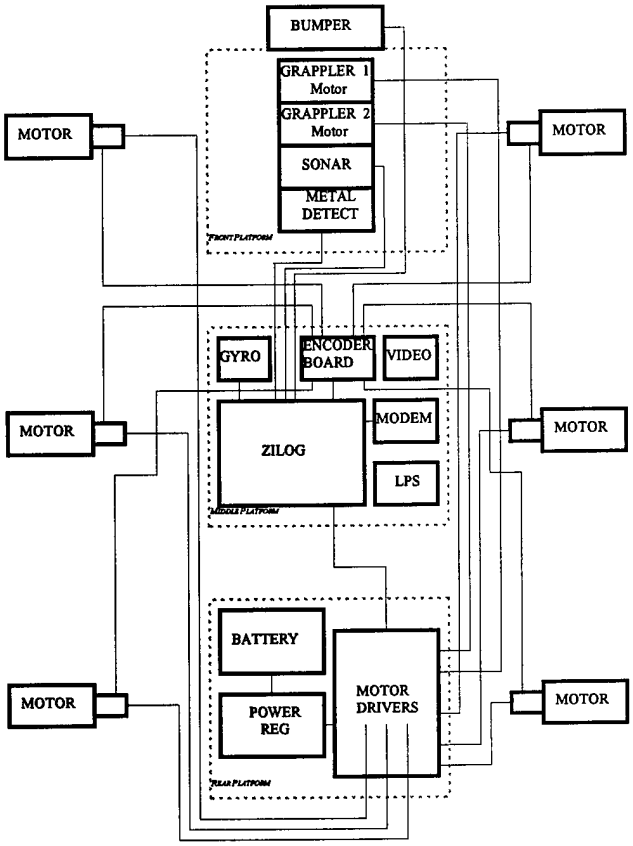


Figure 9: Schematic showing sensor and electrical hardware placement.

The gyro is the first step towards a modular, distributed processing design using sensors with built-in microprocessors. The local microprocessor runs the low level, hardware driver interface code which abstracts the main processor from the hardware implementation. This allows changes in the hardware implementation without changes in the high level control code. The local microprocessor also processes the raw sensor data into compact readily-useable information packets. The gyro microprocessor, for example, processes raw sensor voltage into heading information. The advantage of this modular design becomes apparent when all the modules use a common bus interface. This allows any device to be attached in a daisy chain fashion without additional I/O ports. Each device uses a unique address to allow the main

processor to communicate with the device. With a local microprocessor doing much of the data processing, the bus can be implemented with a serial communication protocol.

The numerical integration of the rate gyro often leads to a drift error if integrated over an extended period of time. Intermittent software re-calibration is performed by tracking position change with the LPS and correlating the movement with the readings from the gyro.

3.2.2 Laser Positioning System

Using a dead reckoning scheme for vehicle navigation eventually leads to the buildup of absolute position error. In order to resolve these navigational errors, an absolute positioning system should be used as a verification of the dead reckoning results. The Draper SMART system accounts for these inherent errors using a laser positioning system (LPS)[5].

The LPS provides a check on BUG position using two synchronized laser beacons and onboard transponders (See Figure 10). Knowing the distance, l_1, between the two beacons, the angles θ_1 and θ_2 can be calculated based on the timing sequence provided by the vehicle transponders. This system uses basic triangulation to provide absolute position information of the BUG.

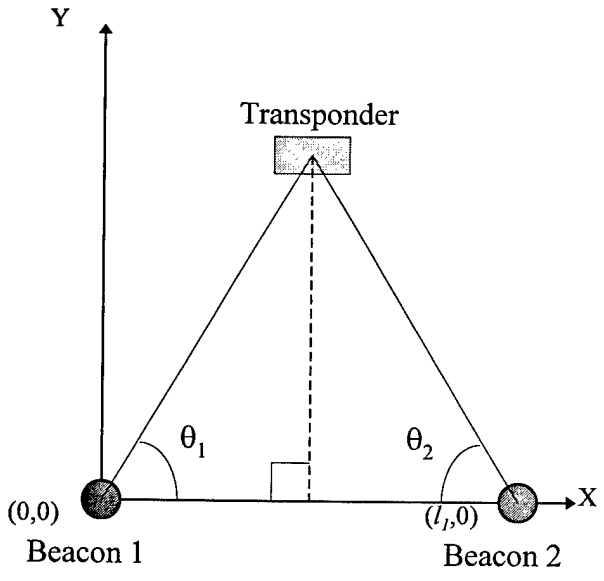


Figure 10: Laser Positioning System (LPS)

[5] CONAC™ Vehicle Tracking System, MTI Research Inc., 313 Littleton Road, Chelmsford, MA 01824 (508) 250-4949

3.2.3 Onboard Microprocessor

The SMART system vehicle microprocessor is a 12 MHz Little Giant processor made by Z-World Engineering[6] based on the Z180 microprocessor chip. The Little Giant has 512K of battery backed SRAM, 16 digital I/O lines, 2 serial ports, an 8 channel A/D converter and a 12-bit D/A converter. The Little Giant is programmed with a proprietary variant on the C programming language called Dynamic C.

Programs are downloaded through an RS-232 programming port. Once a program is loaded, the Little Giant can be configured to run the program automatically on power-up. Attached to the Little Giant processor is a PIO96 digital I/O expansion card. This card adds 96 additional digital I/O ports to the Little Giant's 16. The Little Giant is very simple and quick development platform and is excellent for small embedded projects.

4. System Software & Control Station

4.1 Control Software

The control software for each BUG is designed with several important goals in mind:

- Easily modified
- Easy to test
- Expandable
- Flexible division of labor between vehicle and remote control station

4.1.1 Layer Approach

These goals are achieved by dividing the software into "layers". Each layer is dependent only on the code in layers below it. This restriction on dependencies allows the control software to be tested from the bottom up. Since changes to the software affect only those layers above, modifications to existing code are much more straightforward.

The software layers have an additional benefit of allowing the division of labor between the BUG and control station shift as necessary. Possible configurations are: control station does nearly all processing, control station handles only task management and mission control, or control station handles only high-level mission control.

[6] Z-World Engineering, 1724 Picasso Avenue, Davis, CA 95616 (916) 757-3737

Because testing an embedded system can be difficult, a full simulation of the vehicle and its control software can be run on the control station. This simulation is identical to the vehicle's control software down to the driver interface level.

4.1.2 Concept of Tasks

The control software provides a skeleton for which high-level tasks can be written. Tasks enable the BUG reach a simple goal, such as navigating to a point, performing an area search, or picking up a UXO. The control software skeleton does the majority of the work, making task design a fast and easy process. The overall control software system can be easily expanded by adding additional layers or tasks as necessary.

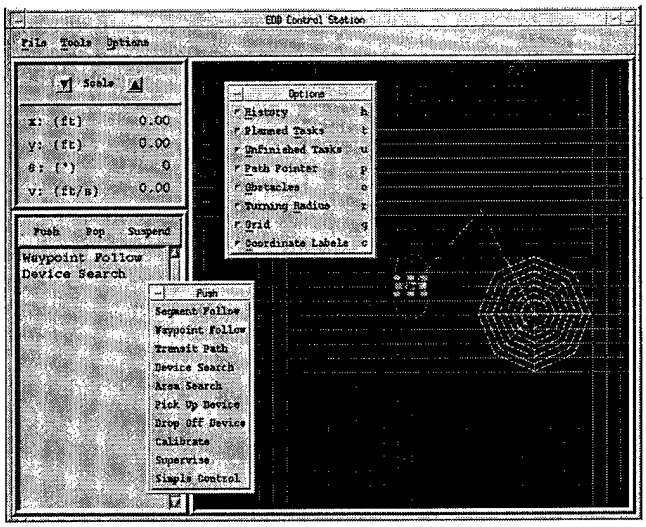


Figure 11: Control station GUI showing tear-offs for the map overlays and available mission tasks.

4.2 Control Station & GUI

4.2.1 Hardware

The SMART system control station runs on a Pentium desktop PC under the Linux operating system. This platform is less expensive than more specialized systems, but provides ample 32 bit computing power for this application.

4.2.2 Control Station Software

The control station software is written in ANSI C using the Xwindows and Motif libraries for Linux. These libraries provide the building blocks for a clean, easy-to-use graphical interface with the vehicle.

The main interface to the vehicle is the mission control window (Figures 11 & 12). This window displays an overhead view of the BUG's surroundings, the current task stack, and the current position, heading, and velocity of the vehicle. The overhead view has multiple overlays which can be hidden if necessary to reduce screen clutter. These overlays include:

- Obstacles
- Sonar Hits
- Path History
- Planned Tasks
- Map Grid

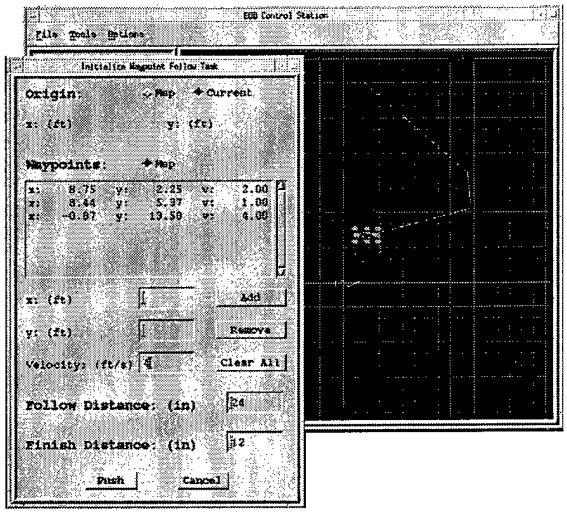


Figure 12: Control station GUI implementing a waypoint-follow task.

Tasks can be pushed onto or popped from the task stack from the mission control window. When a task is being added to the stack, a task creation window opens and displays the task parameters. If the planned tasks overlay is visible, the mission control window will display the proposed task as the parameters are changed. The available tasks include:

- **Segment Follow** - Attempt to follow a straight-line path between two points as closely as possible.

- **Waypoint Follow** - Execute multiple connected segments in succession.
- **Transit** - Plan a series of waypoints to a desired location which avoid known obstacles.
- **Area Search** - Traverses an area using a search pattern and attempts to detect UXO.
- **UXO Pickup** - Pick up a UXO with the grappler mechanism.
- **UXO Dropoff** - Drop a UXO held by the grappler mechanism.
- **Simple Control** - Allows the user to take direct control of the vehicle.

The control station also includes a debug window. This window displays all state information for the BUG such as: steering position, wheel velocities, onboard system status, and battery charge.

5. Simple Mission Strategy

5.1 Basic Assumptions

It is assumed that the locations of the UXO within the area of operation are known *a priori*, but that the terrain conditions are not. The destruction of the gathered UXO in the ODA is not addressed directly, although a camera will be positioned in the ODA for remote examination of the deposited UXO before a human technician places a detonation charge.

The locations of the UXO initially are assumed to be known within a 1 m^2 area, but development work will attempt to relax this requirement as appropriate. The starting UXO position information is assumed to come from a manual visual sweep until appropriate detection sensors are available for automated UXO survey vehicles. A remote method to register the location of the detected UXO will be provided.

5.2 The PUCA Operation

5.2.1 Path Planning

Using the control station, the operator submits a waypoint-follow task to the BUG which commands the robot to travel to the approximate location of an UXO (within 1 m^2). The control station then uses the A^* [7] search algorithm to plan the most efficient path to that location, given the initial obstacle information.

The A^* search is a method of finding a minimum cost path between any two nodes of a cyclic graph. An A^* search differs from other search algorithms in that the cost associated with a particular node in the solution includes an estimate of the cost (called the heuristic) to complete the search (i.e. to reach the objective node from the current node). By proper selection of the heuristic, trade-offs can be made between the optimality of the solution and the time required to generate the solution. In particular, by selecting a heuristic that is guaranteed to always underbound the actual cost to complete, it can be shown that the A^* search produces an optimal solution.

An example solution of an A^* search using an occupancy map is shown in Figure 13 with obstacles mapped in the mission area. The environment is broken up into known empty, known occupied, and unknown (yet to be mapped) regions. The planning problem is to provide an obstacle-free path from the start node, S, to the goal node, X. The planner returns the shortest obstacle-free path, minimizing exposure to unknown areas when known empty areas are not available. Figure 14 shows the implementation of the A^* search on the graphical display of the SMART control station.

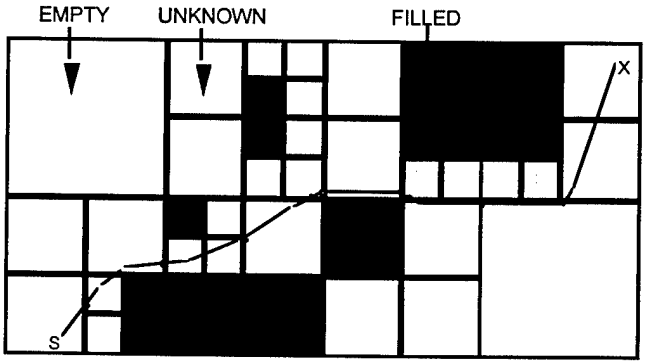


Figure 13: Route planning using the A^* search algorithm

[7] Judea Pearl. Heuristics: Intelligent Search Strategies for Computer Problem Solving. Addison-Wesley, Reading, 1984.

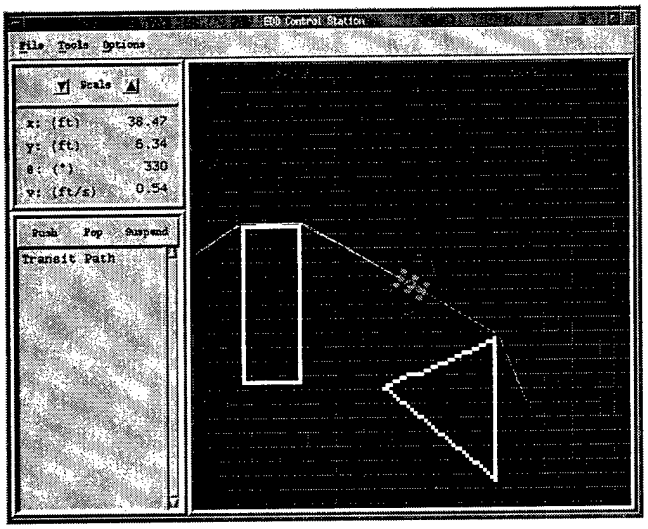


Figure 14: Control station GUI showing implementation of the A* algorithm.

5.2.2 Navigation & Dead Reckoning

Navigation to the coordinates of the approximate location of the UXO to be recovered is accomplished using a combination of a dead-reckoning scheme, and the LPS for an absolute reference. Dead reckoning is accomplished using the steering and wheel encoders in combination with the gyro. The motor encoders give the total distance traveled, while the gyro gives the angular position of the robot. The dead reckoning scheme resolves the measured heading and wheel motions to the motion of the center platform of the BUG.

The strategy for dead reckoning is to discretize time into specific intervals. Knowing the time elapsed between readings (the value of the interval), and the updated distance and heading information, the current speed, position, and heading of the BUG can be calculated. Errors accumulate due to the fact that each interval requires information from the previous interval for calculations. Any slight errors are magnified at each discrete time step. This is the reason that an absolute position system, one with a fixed reference frame, must be used as a periodic correction.

5.2.3 Map Building

During transit, the control station maintains the updated coordinates of the BUG as well as the locations of known and newly discovered obstacles. This information is continually updated and allows for the real-time construction of a map of the mission area. This map logs the locations of obstacles known a priori, obstacles detected during transit by the onboard sonar array, and the approximate locations of UXO.

5.2.4 Searching

After the vehicle has successfully navigated to the approximate location of the UXO, a search algorithm is initiated in order to precisely locate the UXO. During this phase of the mission, the grappler mechanism is extended in order to use the metal detector to locate the UXO. Then, the BUG follows a series of search patterns until the UXO is discovered. The search routine covers an area over the approximate location of the UXO that resembles a spider's web (Figures 11 & 15).

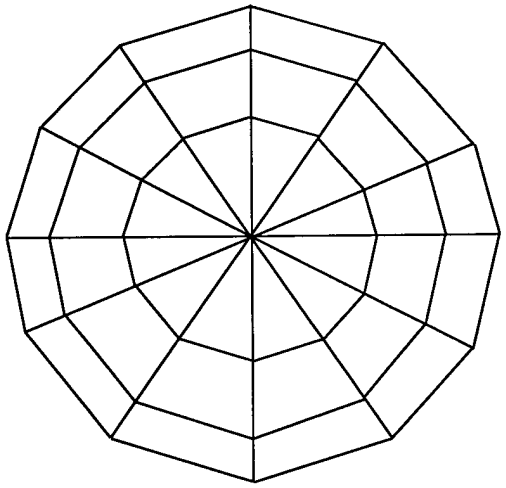


Figure 15: UXO Search Pattern

5.2.5 UXO Acquisition and Disposal

Upon the detection of the UXO in the local search area, another task, the Pick-Up task, becomes active and initiates the retrieval of the UXO using the BUG's grappler mechanism (shown in Figures 7 & 8). Visual verification of the retrieval of the UXO is possible by the use of a small video camera located on the center platform of the vehicle. Once the UXO has been successfully acquired, the vehicle then proceeds to the ODA to deposit the ordnance for eventual disposal. This process is then repeated, given the location of additional UXO to retrieve.

5.2.6 Teleoperated Capabilities

At any time, the operator of the control station may clear the task stack and may assume teleoperated control over the vehicle. This is an important feature that can be used, for example, if the robot is unable to autonomously acquire the UXO after detection during a local search routine. The operator may operate the grappler mechanism remotely, using the onboard video camera as a visual reference.

6. Advanced Strategies

While using a control station and a single SMART vehicle to solve the UXO clearing problem is effective, it is not the most efficient solution. The IUVC is continuing its research toward more advanced and efficient strategies for UXO retrieval using multiple BUGs, environment mapping, "roadway" building, and by determining the optimal distribution of processing power between the robotic agents and the control station.

6.1 Multiagent Approach

Using more than one SMART vehicle to perform PUCA and BIP operations in UXO clearing scenarios is a challenging task.[8] There are, however, advantages to using more than a single BUG.

UXO clearing using multiple robotic agents enables the mission to proceed at a much faster pace - more than one UXO can be retrieved at a time. At the beginning of the mission, each agent is assigned a specific target UXO to either retrieve or blow in place. This allows for a divide and conquer approach to the mission.

Due to the hazardous environment in which the BUGs are required to operate, multiple vehicles also enable the SMART system to proceed with the mission in the event that individual vehicles are damaged. This requires control station capabilities to re-plan the mission using the available agents. This mission planning and re-planning strategy is currently under development in the IUVC.

Finally, individual sensor data from each BUG can be assimilated into a global map for the entire agent community to reference. Using local information from each vehicle enables the control station to quickly create a global picture of the mission area. This information can be used to log locations of obstacles, additional UXO, and safe zones - those areas free of UXO. The control station, therefore, is capable of building an environment map that includes safe roadways for BUGs to use while in transit.

6.2 Map Building & Roadways

Using the sensor information from individual BUGs to create a global map of the mission area that includes safe roadways has important implications in the overall strategy for efficient UXO clearance operations. In order to avoid obstacles and navigate through an unknown environment, each vehicle must proceed at a slow pace while in transit to and from the approximate UXO location and the ODA. This process is expedited using roadways.

During the mission, the control station is capable of logging the paths followed by each vehicle. These paths, because they have already been traversed by an agent, can then be declared as roadways. As a BUG encounters one of these roadways (current coordinates of the BUG coincide with a previous path), it is capable of proceeding at a much faster pace due to the fact that the path should be free of obstacles and UXO. This procedure, however, does require that the unknown environment is somewhat static.

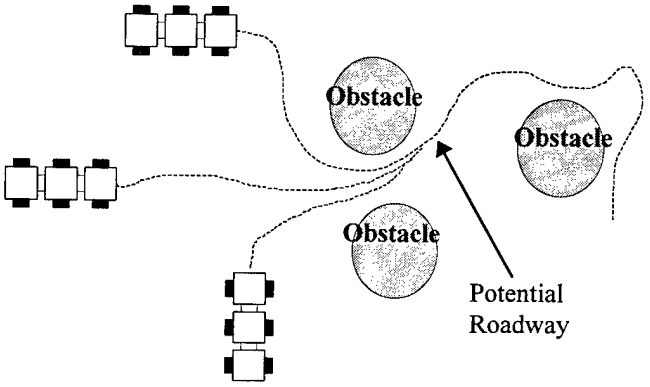


Figure 16: Environment map showing locations of obstacles and a potential roadway.

This approach enables the robots to operate in a slow and a fast mode of travel. The slow mode is used when defining the map and when traveling "off-road." The fast mode, however, enables the robots to travel at higher speeds which contribute to an overall mission completion time that is much faster than without the roadway system.

6.3 Distributed Processing

The IUVC is also interested in determining the optimal allocation of computational resources among the autonomous vehicles and the control station. Questions arise such as, "Should the control station provide the bulk of the computational effort, dictating commands to the robotic community? Or should each agent be responsible for maintaining its own view of the environment and mission goals?"

Arguments arise for each question, as there are certainly tradeoffs in each situation. Giving the control station the bulk of the computational duties allows for the creation of simpler, smaller, and inexpensive agents. It is much easier to add computational power to a single, stationary control station that to each individual BUG. However, if the

[8] Marcus J. Huber and Patrick G. Kenny. The Problem with Multiple Robots. *American Institute of Aeronautics and Astronautics, Inc.*, 1994

control station is damaged, the entire system is rendered useless.

This would not be the case, however, if each agent were given ample computational resources to carry out its part of the mission in the absence of the control station. However, the complexities of inter-agent communication and the additional hardware and software needed on each vehicle make this a much more complex issue. The optimal distribution of computational resources would be one that combines the best of each extreme.

7. Parallel Development

While developing the current UXO clearing system, the IUVC has also been looking ahead to create the next generation SMART system. This advanced system includes upgrading to a new vehicle microprocessor (x86), realizing the capabilities of the Global Positioning System, and using a new serial bus architecture (I^2C).

7.1 Microprocessor Upgrade

Limitations on the processing power and the development language of the Little Giant processor has forced a migration to a more powerful platform in order to perform more complex behaviors. The proposed platform is the x86 or the Intel PC architecture. The x86 processor will allow the choice of many operating system environments such as DOS, UNIX, Linux and QNX. The new processor will also increase the processing power from a 12MHz Z180 to a 50MHz 486DX as well as allow the use of off-the-shelf components such as flash drives, Ethernet interfaces, PCMCIA interfaces, etc.

7.2 Global Positioning System

In addition to the dead-reckoning scheme and the LPS used for absolute positioning, the IUVC is also integrating the Global Positioning System (GPS) for use as an additional navigational aid.

A Premier® differential GPS system is being used. Differential GPS is implemented by obtaining coordinate information from orbiting satellites and correcting errors in the position estimate through the use of ground based reference points.

This system does not eliminate the need for the LPS, however. Heavy cloud cover or satellite positioning may make it difficult to acquire the satellites needed to obtain positioning information. In these situations, the LPS - a ground-based absolute positioning system - provides an adequate check on dead reckoning errors.

7.3 I^2C Serial Bus Architecture

The current architecture has custom parallel interfaces for each device. This architecture requires a large number of wires making assembly, maintenance and repair difficult and time consuming. The proposed change in architecture will replace the large number of parallel wires with a two wire serial bus. Sensors and actuators will be modularized and connected in a daisy chain fashion along the two wire bus. The x86 processor will serve as the master and control the flow of data on the bus. Each device on the bus will have a unique 7-bit address.

The two wire bus will greatly reduce the amount of manual labor involved with manufacturing and assembling a vehicle. A problematic device can be debugged by simply detaching it from the network and testing it in a stand-alone environment. In the current architecture, each device has a custom interface requiring a custom test setup. With the proposed architecture, each device will have a standard two wire interface allowing the same test setup to be used for all devices.

To counter the reduced bandwidth of serial versus parallel data buses, each module will process the large amounts of raw sensor data into high level data. Each module will contain an embedded micro-controller dedicated to process the raw data as well as run the low level hardware interface code. Already in place in the current architecture are dedicated, embedded processors that control the sonar and the gyro. With sensor and actuator software being executed locally at the sensor or actuator, the main processor is free to perform other tasks such as path planning unencumbered by the processing needs of low level hardware drivers.

8. Conclusions

The IUVC is now using the SMART system to solve the problem of clearing unexploded ordnance in unstructured environments. The base system includes a control station, a small, autonomous robotic vehicle, and an absolute positioning system. Continued improvements and developments to the system include: the addition of GPS; upgrading to a new vehicle microprocessor and serial bus architecture; and the use of multiple agents.

The IUVC's rich history of small autonomous robotics and smart system technologies is the driving force behind these advances in EOD operations. The center plans to continue to leverage these competencies in its efforts to provide a safe and effective means of removing humans from the dangerous situations encountered when attempting to clear unexploded ordnance.

Enabling Techniques for Swarm Coverage Approaches

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Helen Greiner, Colin Angle
Joseph L. Jones, Art Shectman

ISX Corporation
Richard Myers

Abstract

The use of multiple low cost robotic mine hunters to provide rapid and complete area coverage represents a promising new approach to the counter mine problem. With this approach, however, comes a new set of problems for the effective implementation of this technique. How can a lightly trained technician operate such a complex system? How much of the terrain of interest in inaccessible due to trees, rocks and bushes? And how can I be sure that the robots have done their job? By augmenting our Behavior Based local navigation software with a supervisory control interface and a GPS mapping and directed search engine, IS Robotics has developed a swarm control system capable of operating large numbers of hunter vehicles. We have also developed the mine hunting vehicles with embedded intelligence capable of fully utilizing this control system. The machines integrate local terrain sensing, high accuracy GPS, robust mobility, support for task specific sensors, computational assets, and power systems in a cost effective manner.

Fundamental to the Swarm approach is the assumption that large numbers of vehicles can operate in parallel with little or no operator interaction. Simple intelligence schemes have been shown in simulation to produce exciting results, but the real world offers far greater challenges. Unfavorable combinations of obstacles, terrain slope, and poor traction can introduce systematic effects into "random" search. Such effects eliminate any guarantee of complete coverage by a robot using random search. Directed search, search based on global methods, can produce superior results by working from an explicit representation of areas covered verses areas not covered. However, even directed search coupled with onboard intelligence does not solve the whole problem.

Despite great advances in navigation and other technologies, the challenge of continuous duty unsupervised operation in natural environments has not yet been met. Eventually, a robot that attempts total autonomy will be stymied by an unplanned condition or a pathological combination of obstacles or other hazards. Our approach is to add a layer of software that 1) monitors robot progress to detect such conditions and 2) alerts the operator and allows him or her to intervene. This method produces a robust system that places infrequent demands on the operator and reduces the robot design challenge to a manageable level. We show that a production system can be manufactured at an acceptable cost.

1. Introduction

Technology that will largely eliminate human risk in mine clearing is at hand. This high level of risk reduction is becoming possible because of advances in microrover, positioning system, communication, and mine detection and neutralization technology. In this paper, we will describe several components of the new technology important to the mine remediation problem. Features of a control structure that utilize this technology effectively are detailed. In addition, we review two IS Robotics experimental robotic mine countermeasures systems that bring the required technology and control together in one package.

This automation assisted mine remediation is the natural "next step" to current hand-held detection systems and remediation practices where humans come in proximity of UXO. In designing an automation assisted mine remediation system, a control structure for the complete system must be developed. This control structure must make the new remediation system a tool that a technician can use effectively. As such, we need to recognize mine countermeasures (MCM) operational requirements, allow for human supervision and control when desired, and incorporate current mine hunting doctrine.

IS Robotics has developed a control structure for MCM operations that is based on the following important capabilities:

1) Supervised Autonomy (operator may take control at any time)
2) Graceful Degradation (tolerates failures or noise on terrain sensors)
3) Spatial Coordination of Sensor Data (improves detection and reduces falses positive rates)
4) Certifiable Coverage (reports to operator that an area was cleared)

Automated Systems without these features will lack the functionality and robustness to effectively assist the MCM technician. Consequently, the system will have little chance of being incorporated into a military mine countermeasures doctrine.

Many MCM scenarios would benefit from automation. These scenarios include: mapping, marking, Pick Up and Carry Away (PUCA), and Blow in Place (BIP) operations. IS Robotics is currently working on two such systems. The first system is FETCH, a munitions countermeasures system that is part of the EOD BUGS Program. Fetch has demonstrated all components of the full system in a cluster munition PUCA operation. It has demonstrated placement of a simulated shape charges for a BIP operation. The second system is Hum-De, a joint Tracor/Tracor GDE/IS Robotics Internal Research and Development project, which concentrates on mine detection, mapping and marking. The Hum-De Program combines an IS Robotics mobile platform and the MCM control structure with state-of-the-art Tracor GDE Systems sensor detection and data processing (recently selected for further development under the HSTAMIDS Program.)

2. Current Mine Hunting Doctrine

2.1 Buried Mines

In order to understand automated techniques it is important to recognize current mine hunting doctrine. In this paper, we use the term MCM Engineer (Mine Counter Measures Engineer) to mean Army Combat Engineers, EOD technicians, or other personnel involved in mine remediation. MCM Engineers currently sweep minefields by walking the length of the field with hand held pulsed induction mine detectors. The reliability of this equipment depends on environmental conditions. Excessive

metallic content (bullets, shell casings, frag) in the ground must be filtered out by reducing the sensitivity of the detection equipment. At some point sensitivity reduction compromises the effectiveness of the detector and manual methods must be used.

If the engineers locate a potential mine, they attempt to identify it using a fiberglass stick. These sticks are pushed into the ground at a 35 degree angle until the stick hits an object. The angle ensures the stick hits the side and not the top of the mine. An object discovered in this way must be dug out in order to ascertain its identity. The mines are normally buried approximately 4" below the surface, if they were deeper and they would not be effective. Because they are not buried deeply, the probing need not be very forceful.

Once identified the mine is either blown in place, removed and burned, or simply removed. Blowing in place is common, but in some cases, such as urban neighborhoods, the environment is not suitable for a high order detonation. Blowing in place is currently carried out using anti-mine shape charges. Burning of the mine is preferable as it greatly reduces collateral damage due to fragmentation. Using this method, the detonation potential is reduced by destroying much of the bulk charge before the detonator fires. Removal of the mine is the most environmentally friendly method, but it is also the most time consuming and dangerous. All three of these methods are being employed in Bosnia. All can benefit from automation.

2.2 Munitions

The clearing of unexploded sub-munitions (such as M41 anti-tank munitions) from a battlefield is particularly dangerous due to the large number and small size of these objects. The unpredictable state of sub-munition fuses due to ground impact and exposure to the elements also complicates clearing operations. Also, unlike buried mines, sub-munitions are found using visual inspection and not metal detectors. Just as buried metallic debris can cause problems for metal detectors, any debris that clutters up a field will make visual identification of munitions more tedious.

One method for clearing a field of sub-munitions has MCM Engineers walk shoulder-to-shoulder at two arms lengths apart across a swath of the field to be searched. As sub-munitions are identified via visual inspection they are marked with flags. Non-explosive debris can also picked up to make a second inspection easier. Unfused high-explosives may also be collected and piled near marked sub-munitions. Because of the risk of detonation, sub-munitions are not handled unless absolutely necessary. After all munitions have been marked, shaped charges are placed at each and connected by flash cord. The munitions are then blown in place simultaneously from a safe distance. Although this procedure was observed during a range clearing operation at the Twenty-nine Palms Marine Base, it may not be relevant for all situations.

3. Technology

Recent technological advances are, for the first time, making possible automation assistance in the mine clearing problem. In the past, integrating all requisite capabilities into a man-portable, low cost package was not feasible. We feel that systems should be designed with available technology as field testing in real conditions is the only way to determine what the true operational problems will be. As sensory systems and embedded intelligence programs improve, increasingly difficult terrain and more challenging circumstances such as canopy cover will be targetted. Approaches that argue for limited sensory capabilities and no global position information need to be seriously questioned as to their operational value.

1) Positioning Systems
Positioning systems let the rovers cancel drift in their perceived location and allow pattern based search strategies, and, more importantly, they allow the creation of a coverage map. Carrier Phase Differential GPS systems are giving accuracies of <1 inch under ideal conditions. These off-the-shelf systems are sufficient for a variety of terrains such as beaches, fields, and desserts. In terrains with canopy cover, buildings, or other occlusions, alternate positioning systems may be swapped in. For these areas, laser position systems[1] and RF localization methods are available. A more advanced ultra wide band radio approach is under development for the military. This system, if the production version achieves preliminary specifications, more than meets the requirements for UXO cleanup operations. It features good penetration characteristics claiming range/accuracy of 1 km with 3 inch accuracy non line-of-sight (LOS).

2) Microrovers
The size, weight, and footprint of microrovers combine to give the devices a very low surface pressure thus minimizing the risk of accidental detonation of pressure mines. IS Robotics is in the business of designing and building microrovers for applications such as reconnaissance, surveillance, planetary exploration, research, mine countermeasures, and hazardous material handling. We have proven that sophisticated systems with embedded intelligence can be man portable, and thus microrovers are now considered feasible for many more applications. Microrover make use of developments in a wide variety of domains such as increased battery capabilities, electronics miniaturization, improvements in connectors, and sensor system developments.

3) Mine Detection Systems
Under the Hand Held Standoff Mine Detection System (HSTAMIDS) and other programs, the detection rate for non-metallic anti-personnel mines has increased from virtually no capability prior to 1990 to near 70% probability of detection.[2] In the coming year, this program will focus on multi-sensor integration, detection algorithms development, and enhancement in user interface. We believe the technology developed under this program can be effectively used by automated vehicles.

4) Multichannel Communication Systems
Advances in spread spectrum technology allow large numbers of robots to communicate all using the same frequency band. Commands and data can now be effectively shared with a base station and thus other agents. (However, compared to purely teleoperated devices, systems using supervised autonomy need less communication bandwidth)

5) Neutralization
Blow in Place (BIP) neutralization techniques are proving both performance and cost effective. For example, Tracor's mine neutralization shaped charge is a recently developed and field demonstrated shaped charge explosive device proven effective against all known mines. They are capable of penetrating through several inches of soil or water to destroy buried or submerged mines in-situ without site preparation.[3]

Continuing trends in cost reduction of advanced technology and production scale manufacture will reduce the sale price of capable vehicles. In fact, the European Joint Research[4] center sees vehicle deployment as the only way to meet cost effectiveness goals set by the United Nations.

4. Enabling Techniques

4.1 Supervised Autonomy

In the Supervised Autonomy paradigm, rovers are designed to perform autonomously under most expected circumstances. A sophisticated behavior control program allows the rovers to

perform a mission while responding to real world conditions (note: behavior control is described later in this paper). However, to increase system reliability and operational control, Supervised Autonomy allows a MCM technician to take direct control of the rover whenever he needs or desires. We recognize that the current state of artificial intelligence coupled with sensory limitations precludes rovers from autonomously dealing with every contingency. Unexpected terrain features or other pathological conditions may cause failure in the automated routines. The supervised autonomy approach reduces the rover control system design challenge to a manageable level.

The supervised autonomy control paradigm yields many other important benefits. First, it allows selective intervention. The operator has the ability to directly control all rover motions at any time if desired. The second advantage is in force multiplication. Mine countermeasures is a task that lends itself to parallelization. Since direct interactions with the rover by the combat engineer are infrequent and brief, a single operator can supervise an entire swarm. Thirdly, multiple inexpensive devices operating together insure redundancy and have the potential to reduce cost per acre covered.

4.2 Spatial Coordination of Sensor Data

Having the best sensors is not enough. How those sensors are used to collect data can dramatically impact their effectiveness. Mounting a sensor on a robotic platform capable of tracking its position precisely opens the door for a host of new and powerful Automatic Target Recognition (ATR) algorithms. This is due to the robot's ability to accurately control the sensor's position and coverage rates. The system also has the potential to accurately collect very high sensor data densities. The following section looks at opportunities a robotically controlled sensor, such as the Hum-De, can give.

4.2.1 Differential Data Techniques

A powerful method for improving the signal to noise ratio from the sensor in mine detection applications is to differentiate the stream of data. This differentiated data strongly shows where step changes in readings occur, while tending to filter out slow changes and steady state value. Since a mine is a discontinuity in the normal soil, differentiated data should contain less noise and stronger relevant signal information.

If in collecting data, the sensor is not moved at a uniform speed across the ground or the sample points are taken too far apart, the ground's slow characteristic variations can appear much larger or abrupt than they actually are. This complicates the interpretation of the differentiated data and causes false indications of sub-surface anomalies.

These effects can be minimized through the careful control of the sensor, and by ensuring a tight and consistent grid of mine sensor readings. Specifically, the sensor should move at a uniform rate across the ground, and sampling of sensor data should happen at fixed intervals such that each data point is within a small distance of the last. The characteristics of the terrain will determine the maximum allowable distance between measurement. It is likely, in some terrains, that this maximum distance will be large compared to other sample frequency constraints described below.

4.2.2 Geometric Techniques

The use of geometric analysis techniques for the localization, classification, and rejection of false targets has been minimal in the dismounted and vehicular mine

hunting domain. The use of geometric methods in dismounted operations is currently left entirely in the hands of the combat engineer or EOD technician. Since it is difficult to predict or assume any advanced spatial ability in a given soldier (or anyone else), use of any geometric algorithms is very limited. Vehicular mounted mine sensing arrays have the ability to collect spatially correlated sensor data. However, due to the arrangement of the sensors, resolution is a problem (there do not exist arrays capable of collecting spatially correlated sensor data better than data lines separated by 6"). This severely limits the use of geometric techniques against all but anti-tank mines, and even there, severe limitations exist.

A sensor control system which allowed the collection of data in fine position correlated arrays would open up a new set of powerful tools for the detection and classification of mines[5]. Algorithms designed for image processing could be brought to bear on such data. The symmetric or otherwise characteristic shapes of land mines could be used to reduce false positive detections, and more accurately determine the position of a mine. There currently exist innovative ways of disabling mines through the use of shape charges which cannot practically be used in many instances due to the uncertainty of mine location. Geometric techniques could solve this problem and pave the way for complete robotic demining solutions.

4.2.3 Parameter Optimization

Many mine detection sensors have operational parameters which affect the way they collect data. In the case of Pulse Eddy induction sensors (PE), the magnitude and shape of the current pulse, the gain of the detection amplifier, and potential analog and digital filtering of the return signal are all variables. GPR sensors have a host of similar parameters including the frequency of the emitter.

Most parameters have been optimized for a general case situation, while others can be manually adjusted to calibrate the sensor to a given terrain. This is a practical solution, but not an optimal one. In order to do better, the sensor needs on-board intelligence which looks at a sensor's readings (and potentially other system sensors), and determines a new sensor parameter set to use.

The system would also have to have the ability to go back and rescan an area in such a way that the results of the first scan were spatially calibrated with the second. This correlation will allow more sophisticated algorithms for data processing to be developed. Specifically, a high sensitivity setting could be used to ensure that a target was not missed, but once found, this high sensitivity setting would not yield suitable geometric shape or mine centroid information. By reducing the sensor's sensitivity and rescanning the area, a more accurate target shape may be found. Additionally, multiple sensor runs can be differenced and changes based on parameter adjustments between runs can be found. Since different materials absorb EM energy differently at different frequencies, this parameter differencing technique may be very powerful in classifying potential targets.

4.3 Graceful Degradation

Graceful degradation means the ability to function at a reduced level of performance in the face of noisy signals, sensor failures, or unexpected conditions. Graceful degradation is a key feature (arguably the most important feature) for an autonomous system. Most biological systems exhibit graceful degradation to the extent of functioning with loss of limbs or complete loss of sensory systems. To exhibit graceful degradation, robotic vehicles need to be designed from the bottom up[6]. They need to be more than just cars or tanks

with sensor packages tacked on. Graceful degradation is facilitated by a behavior control approach, a robot control architecture proposed by Prof Rodney Brooks of the MIT Artificial Intelligence Laboratory[7].

Behavior programming is a decomposition of the robot control problem. Rather than separating the elements of robot control into a sequence of functional steps, a behavioral control program decomposes the problem into a number of task achieving behaviors all running in parallel. The control software in a behavior control robot can be simpler to design because the behavior modules are task specific and, individually, need not be made general purpose.

The behavior control approach depends on layers of behaviors that perform redundant functions. The most effective way to explain this is with an example. Imagine a rover commanded to perform a search for munitions in an area. The rover comes to a boulder blocking its path. Under most conditions, proximity sensors (IR, sonar, or laser) sense the blocked path and the rover goes around the boulder resuming its course on the other side. However, now imagine the boulder instead a small bush, the rover comes to it and the IR fails to detect it. Luckily, redundant sensing allows the sonar to sense it and the rover succeeds negotiating around. To further thwart our attempt, now the sonar fails to sense the bush because it is positioned too high. The rover hits the obstacles; tactile sensors detect it. Tactile sensing is an integral part of any autonomous system. Using these readings the rover can "bump and turn" around the obstacle. This list of possible failure modes and backup systems can be extended to include stall and velocity sensing on the drive wheels, inclination sensors, and impact sensors.

Behavioral programming doesn't depend on a particular sensor to be absolutely reliable under all circumstance, rather we depend on many types of sensors to provide redundant sources of information. Compared to traditional sensor fusion approaches, the cost sensors and computational requirements of employing sensor data is reduced in a behavioral control system. Bumping an obstacle while attempting to skirt it, as the robot does in this example, may not be the optimal. However, such a strategy usually works -- hence the term "graceful degradation".

4.4 Coverage Certification

4.4.1 Coverage Map

One important task of a mine countermeasures system is to provide military personnel with assurance that an area is cleared. System designs should output coverage maps. A realistic example output would show that the rover had swept Area $A1$ with a Ground Penetrating Radar and a Pulsed Eddy Induction sensor at a rate of V and height H. A map of the area covered would be provided with potential mines clearly indicated. Just as importantly the final map will clearly demark areas not covered. Sensor readings and visual images from the rover will give an indication of why the areas were not covered. Reasons for non-coverage could include bodies of water, terrain taxonomy that is too difficult to obtain accurate readings, excessive metallic clutter, or dense brush. This information is vital in evaluating how sweeping should progress.

4.4.2 Data Logging

In our approach, a coverage map is created at an Operator Control Unit (OCU). At the OCU, data from multiple assets is integrated into a coherent picture. The system architecture allows for local storage and processing of data and off-board mass storage and archiving.

Local storage of sensory data is important so that the mine countermeasures system

is able to run automatic target recognition routines. Data that would require too much bandwidth to transmit may be manipulated on board.

Off-board storage is essential to provide the coverage map and integrate information from multiple assets. Off-board storage also provides the following benefits:

1) Provides backup in case of accidental detonation
2) Logs "keep away" zones around detected mines and makes this information accessible to all assets.
3) Allows predictive search- Many mine fields are laid out according to known mine doctrine. While this is not the case in Bosnia or most of the Third World, in situations where this practice was followed, knowledge of the location of some mines can be used to predict the location of others. A mine hunting system can keep track of this positional information in such a way that pattern matching algorithms could be easily applied to the data. This approach makes use of the information to improve the speed and ultimate accuracy of a clearing operation.
4) Data on mass storage devices can be saved for later analysis and improvement in algorithms.

5. Advantages of Carefully Designed Automated Approaches

5.1 Risk Reduction

Humans need never enter the mine field. But, their ability to supervise increases the ability of the system to adapt to totally unforeseen circumstances.

5.2 Training

The level of training - or the operator's ability to pick up audio and visual cues that can help indicate the presence of a mine - plays a large role in the detection probabilities in current demining operations. Automatic detection algorithms seek not to replace humans highly evolved, acute sensory systems such as sight, but to augment them with non-intuitive sensory information such as pulsed induction sensors and ground penetrating radar. Performance will be more consistent as reliance of the training and perception skills of individual technicians is avoided for the non-intuitive sensors.

5.3 Force Multiplier

A swarm of rovers are performing the clearance task in parallel. Each rover may be slower than a technician performing the same task[1]. However, since one technician is able to control many rovers, his overall effectiveness is increased. Under supervised autonomy, tasks which vehicles are able to perform well, such as driving a sensor at a constant speed and local obstacle avoidance are left to the robot. Tasks requiring higher level cognitive capabilities, recognition, or reasoning are left to the operator. Under this paradigm, the cognitive load on the operator from each robot is reduced, and he can effectively supervise many rovers. In addition, the rovers can each signal the operator for aid if, for example, the onboard diagnostics signal a problem or if a particular command fails to be completed in the expected time.

5.4 Sensor Data Quality

Human factors, the proficiency of a particular operator to sweep the sensor consistently, currently play a large role in the detection ratios. More consistent application of the sensor yields more consistent results.

[1] Coverage speed will probably be limited by the maximum speed ratings of the GPR and PI sensors. Thus, we expect the operating speeds of the vehicles to be equivalent to that of handheld systems.

Robots excel at scanning sensors at a constant speed on flat terrain. Ability to both drive slowly at a consistent speed and the ability to speed up during terrain traversal is desirable. Position feedback and a well-designed velocity controller are necessary for application of a variety of sensory elements. The robotic approach is expected to surpass current capabilities where sweeping speed is dependent on the proficiency of the operator.

The system could automatically adjust the sensor to maintain a constant distance between ground and sensor element. The combination of sensory systems will allow adjustments to happen under diverse terrain conditions. First, robot level sensors are monitored for terrain bumps. A downward pointing infrared or sonar on the sensing head monitors the gap. In addition, tactile sensing on the scan head allows the scanner to negotiate around obstacles. This approach could surpass a human assets capabilities.

5.5 Automatic Data Logging

Sensory data from positive hits are stored for later analysis. Data logging is automatic and not subject the human error that can be a factor in this highly stressful environment.

6. Examples of Automated Mine Countermeasures Systems

6.1 Fieldable Explosive Target Clearing Hunter - FETCH

6.1.1 Fetch System Concept

Fetch is a proof-of-concept robotic system whose end purpose is to clear an area of unexploded munitions without exposing EOD personnel to danger. Fetch consists of an operator control unit (OCU) and a number of small robotic agents. These robots use a strategy of supervised autonomy to locate, pickup, and carry away unexploded munitions. (A blow-in-place capability has also been shown.)

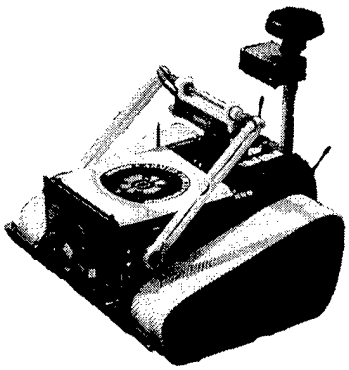


Figure 1 - Fetch Rover

Supervised autonomy allows an operator to direct a robot using a level of control appropriate to the situation. For example, a high level command of the form **Search-and-clear** (*area-A*) might cause the robot to carry out a long and complex set of actions without further attention from the operator. Alternately, the operator may choose to direct the robot at the lowest level by using a joystick to control the robot's motors directly.

The Fetch system is basic, yet complete. Only by building a complete system is it possible to have high confidence that all the important task related issues have been discovered and addressed. Five imperatives guided the development of Fetch:

1. Remove people from danger. This fundamental rationale for developing a robotic munition clearing system requires that the robots be able to perform the entire task. Performance at this level calls for a certain degree of sophistication for individual robots.

2. Make the system reliable. Reliability demands robust behavior in real world situations, simplicity of design,

and the ability of one subsystem to backup another. Fetch includes systems that detect and respond to hazards, a software architecture (Behavior programming) in which system backup is inherent, and a facility that allows an operator to take either supervisory or direct control. Further, Fetch monitors its own progress and can alert the operator if an unexpected condition arises.

3. Make the system easy to use. The OCU provides an intuitive means for the operator to direct many robots. This should reduce the requirements for operator training, minimize operator fatigue, and promote efficient use of operator time.

4. Make the results verifiable. The system keeps a record of the paths of all robots. This allows the operator to verify that any required searches have been completed or to take remedial action if areas have been missed. Confidence that clearing is complete can thus be quite high.

5. Make the system inexpensive. Inevitably, accidents will sometimes result in the loss of robots[8]. Because of this, it is essential to keep the cost of individual robots low. Fetch addresses this issue in part by relying on Behavior programming. Behavior programming has only modest computational needs and can make effective use of simple, low-cost sensors. Further, the moderately expensive positioning and communications systems Fetch requires are likely to decrease in price with time.

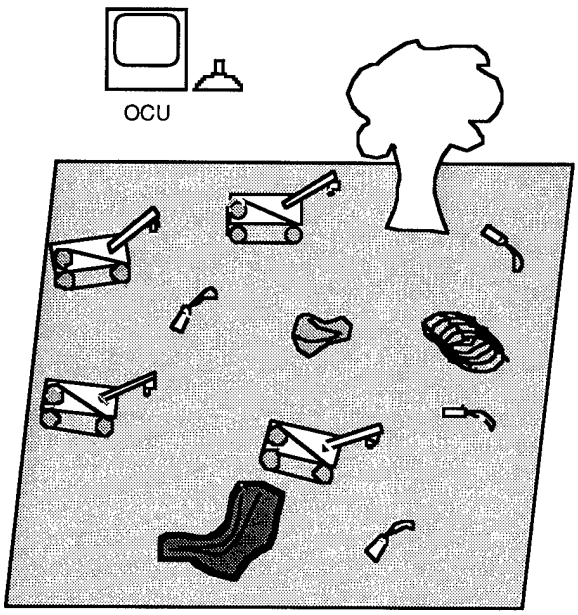


Figure 2 - Overview of Fetch system

6.1.2 Fetch Implementation

To meet these imperatives, we decompose the munition clearance problem in the following way:

Supervision

The supervision component of the system allows the operator to direct and monitor the robots. We developed an Operator Control Unit, OCU, to handle robot supervision. The OCU currently consists of a lap top computer with video card and joystick. A graphical user interface, GUI, has been developed to facilitate operator use. Via the OCU, the operator can issue high level commands to any robot or the operator can take direct teleoperational control of any robot system.

Robot control

Robots are programmed following the Behavior control paradigm. Behavior control facilitates rapid reaction to environmental hazards and robust response to system failures. Further, the modest computational requirements of a Behavior control system help reduce the cost of robots. Robots monitor their own

progress and alert the operator if an anomaly is detected.

Navigation

To direct the robots to known locations of munitions an accurate navigation system is used. This system also allows the operator to verify coverage of any areas that require search. Currently, Fetch employs a carrier phase GPS system that provides two centimeter accuracy under favorable circumstances. Heading information is obtained from a magnetic compass with nominal 2 degree accuracy. Dead reckoning complements the GPS system by providing navigational data to the robot between GPS updates. Dead reckoning can be used exclusively (but with reduced performance) if GPS fails.

Obstacle avoidance/escape

Onboard sensors allow the robot to sense and respond to hazards such as obstacles and rough terrain. Currently, Fetch uses infrared reflective sensors to detect local obstacles. A front mounted bumper monitors collisions and inclinometers measure the slope and roughness of the terrain.

Search

Because the robot cannot depend on precise advance knowledge of munition locations, a search capability is included. This search component consists of a systematic procedure to hunt for munitions and a metal detector to alert the robot that a munition has been found. In operation, the robot spirals outward from the expected position of a munition. If the robot encounters an obstacle in its path, it reflects, i.e. the robot reverses and continues the spiral in the opposite direction. This strategy insures maximum coverage even in the presence of obstacles. If no munition is detected, the search routine stops when the robot exceeds a predefined radius from the start location.

Munition pickup

Fetch includes a rudimentary pickup system. This system is composed of a one degree-of-freedom arm with attached electromagnet. A break beam sensor monitors the area along the bottom surface of the magnet. In this way the robot can determine when it is holding a munition. An automatic munition pickup procedure was developed. To pickup a munition the robot: lowers the arm, turns on the electromagnet, raises the arm, and checks the break beam sensor. If a munition is present, the pickup sequence successfully terminates. If not, the robot backs up and repeats the sequence.

Operator Control Unit

The Operator Control Unit (OCU) implements three major control functions: situation awareness, supervisory control and simple task management. Situation awareness gives the operator a rapid understanding of the status of the Hunter vehicles and of the area currently being searched. We accomplish this by displaying a two-dimensional scrollable map of the search area marked with icons to indicate the relative positions of the robots, obstacles, target munitions and terrain features (see figure 2). A Hunter icon changes color to indicate the current status of the robot; red indicates a fault or lack of progress and green indicates operation within normal limits.

These icons also indicate the heading of the robot and its position relative to domain objects and other robots. The tab key rapidly cycles the focus of attention from one robot to the next. Obstacles detected by the Hunter or manually entered by the operator are displayed as gray boxes with two black crossed lines. Steep parts of the terrain that are detected by the Hunter will be marked as either red or yellow areas, depending on the inclination detected by the robot and areas that have been searched will be marked with open gray squares. When the robot detects a munition, the approximate

location of the detected munition is indicated with a red circle.

By selecting a Hunter icon and clicking the mouse, the operator can issue simple supervisory control commands to the robot. These include a "goto" command which can be issued by placing a flag on the screen which the robot will then autonomously travel to. A Hunter can also be told to "search" an area. This will cause the robot to begin a spiral search pattern, stopping when a munition has been detected. Once a munition has been detected the operator can command the robot to perform an automatic "pickup" maneuver to grasp a munition. The operator can also use the OCU to teleoperate a robot by using either a joystick or keyboard commands and live video transmitted by the robot. This allows the operator to maneuver the robot out of terrain traps, to identify detected munitions and to manually pickup munitions that are difficult to automatically grasp.

System integration

All the above components must be fully integrated in a final system. With such integration in place the operator can bring about a complete clearance operation by issuing a single command of the form: **Dispose** (*robot-designator pickup-location drop-off-location*). Upon receiving such a command, the robot will autonomously navigate to the pickup-location, search locally for the munition, find and pickup the munition, navigate to the drop point, and deposit the munition. All this occurs without further operator attention.

6.1.3 Fetch Results

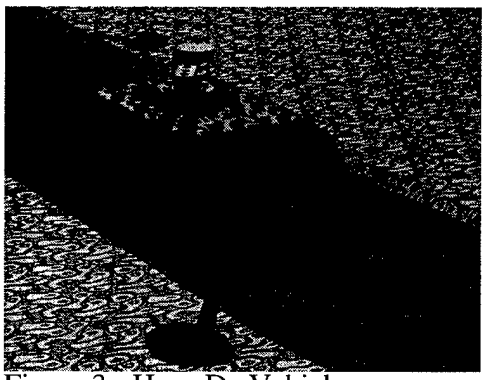
Fetch demonstrated all the above aspects of the munition clearance task at its final evaluation at the EOD site in Indian Head, Md, November 1996. Operating autonomously, Fetch was able to navigate to a given point, perform a local search, find and pickup a munition, transport the munition to the disposal area, and place the munition on the ground. In addition to autonomous operation, high level supervision and direct operator control were also demonstrated.

6.2 Hum-De

6.2.1 Hum-De System

The Highly Mobile Mine Mapping, Marking & Detection System, HMMMM-D or Hum-De, is a joint Tracor/IS Robotics IR&D program to demonstrate remote detection, mapping, and marking of landmines and UXO.

Hum-De is a high mobility platform designed to deploy an advanced GPR/metal detection sensor. The Hum-De platform combines its autonomous navigation system with remote supervision by a human operator through a portable base station. The small mobility platform is only 30" L x 26" W x 14" H and weighs under 60 lbs. The vehicle was designed and fabricated in less than 4 months and is currently being prepared for field demonstration tests.


Figure 3 - Hum-De Vehicle

The Hum-De combines state-of-the-art Tracor GDE Systems sensor detection technologies and data processing onto an IS Robotic mobile platform with unique navigation capabilities and embedded intelligence. The Hum-De system

consists of the the mine detector built by GDE, the Mobility Platform, Sensor Sweep Arm, and Operator Control Unit (OCU).

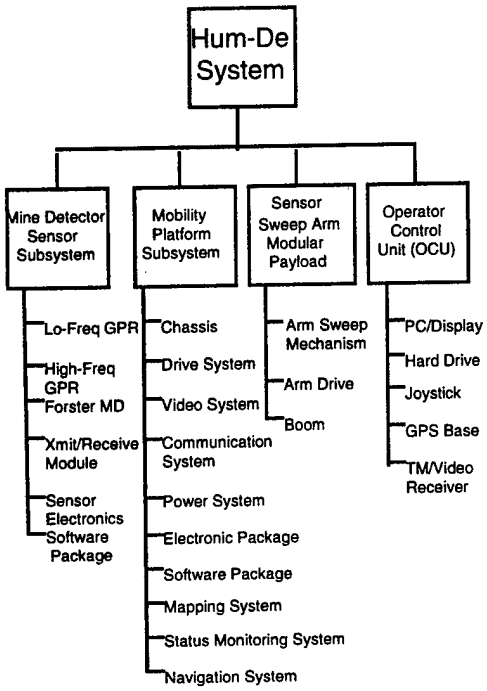


Figure 4 - Hum-De Subsystems

6.3 Expected Results

The Hum-De vehicle is equipped with a combined Tracor GDE GPR/MD sensor on a sweep arm. As the vehicle advances, it gathers spatially coordinated data from the sweeping sensor head. This vehicle can be used as a test-bed for data processing that uses differential, parameter optimization, and geometric techniques. With this sophisticated data processing, we expect significant reduction of the False Alarm Rate (FAR) without significant advances in the combined GPR/MD sensor.

7. Conclusion

Applying automation to the world-wide mine remediation problem makes sense. These systems look toward a future where no human need be sent onto a minefield until it has been cleared of mines. In addition, automated systems have the potential to out perform hand-held systems through precise sensor application and spatial tagging of data. Thus, more effort should be spent on applying the sensing technology to automated techniques.

IS Robotics has demonstrated the control structure for such an automated system with our FETCH Program and have developed an integrated vehicle/mine detector system in our Hum-De Program. These efforts show a proof-of-concept that automation assisted mine remediation is valuable for a certain class of terrain type and missions. As we continue to develop the technology, more variety in terrain and mission scenarios will be included.

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Control of Small Robotic Vehicles In Unexploded Ordnance Clearance

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ABSTRACT

This paper presents the work of several ongoing studies to determine the effectiveness of multiple small robotic vehicles for performing mine field clearance, and the related problem of clearing unexploded ordnance from areas of interest. Many issues are implied in this opening sentence. Not the least of these is knowing, out the many items cluttering a battlefield, which ones need to be cleared. There is the problem of transiting through dangerous areas with the threat of detonation, the difficulties of open field navigation and rough terrain, and the dangerous task of picking up unexploded charges. Current technology employes brute force, is often overt, or the use of human hands - with the potential for loss of life and / or limb.

It is of interest then, to explore whether improvements in safety and performance can be made using small smart machines that have the capability of transiting an open area, obstacle avoidance, and picking up an piece of ordnance, or placing a charge that could be detonated upon command.

Results given in this paper includes the performance of clearance operations with behavior based robots in random search. Included are the effects of the use of multiple vehicles, the influence of various levels of detection probability, and some estimation of the losses suffered under a given probability that detonation will occur upon ordnance recovery.

INTRODUCTION

The Navy's Explosive Ordnance Disposal (EOD) research and development department has recently been active in the pursuit of small robots - a Basic Unexploded Ordnance Gathering System (BUGS) , as an aid to EOD technicians who are required to enter the battlefield , or test firing range, to clear improved conventional munitions(ICM) [1]. The munitions do not all detonate upon delivery leaving about five percent in a dangerous state. Two methods of clearance are to pick up the offending objects and place hem on a pile for later disposal, or to simply blow them up in place. The pick up and carry away scenario is the subject of this study. We will discuss the clearance performance of multiple robots in performing random search.

Since any field of interest will also be littered with obstacles, reliable obstacle avoidance methods are essential, and target detection sensor(s) are integral to every concept. Additionally, candidate robots must have a reliable capability to pick up the selected object and return to the designated pile point.

RANDOM SEARCH

Given a purely random search for unknown targets within an area A, using a perfect sensor of detection radius, r, traveling at speed U, we may assume that the probability of detection is proportional to the mean target density, $\bar{n}(t)/A$, times the area sweep rate [2]. With an imperfect sensor where the probability of detection, conditioned on target presence is p, we can deduce that the expected rate of target acquisition, $\dot{\bar{q}}(t)$ is

$$\dot{\bar{q}}(t) = U(2r)pN(\bar{n}(t)/A).$$

Related to the above, $\bar{n}(t)$ is the average number of targets remaining at time t, so that,

$$\bar{n}(t) = -\int_{\tau=0}^{\tau=t} \dot{q}(\tau)d\tau: \quad \bar{n}(0) = n_0$$

and it is assumed that the remaining are always uniformly distributed - a case unlikely to happen in reality. N is the number of vehicles concurrently involved in the search

Based on the above, the percentage of targets cleared at any time, t, during the operation is given by

$$\bar{n}(t)/n_0 = [1 - e^{-\alpha t}]$$

where the characteristic clearance rate is α, and,

$$\alpha = U(2r)pN/A.$$

The analytical consideration is useful in that it shows the importance of the traverse speed, the detection radius and the proportional influence of the number of robots in the field as well as the importance of a high probability of detect, p.

Random search using cheap robots has been proposed in [3]. In [4, 5], we show that the random search methodology together with a bounding signal (electronic fence) would be possibly preferred for low cost vehicles (without precise navigation) It was also shown that depending on the placement point used, the coverage by multiple robots may be skewed towards the placement point so that multiple placements are desirable. Homing to a pile point can be accomplished with a placed radio beacon

The requirement of having to perform obstacle avoidance maneuvering while in transit adds time to the search. Results have shown that there is an added time consumed by obstacle avoidance (including avoidance of other vehicles) that reduces the effective speed, so that

$$\hat{U} = \gamma(n_o, N)U$$

where γ, is a reduction factor based on the density of obstacles, time lost to obstacle avoidance and the number of vehicles in the search.

EXHAUSTIVE SEARCH

Studies of the threat to robotic clearance systems indicate that the majority of items will be ferrous in nature so that magnetic detection coils could be used to advantage. On a limited size / cost platform, detection radii not more than approximately 20 cm. are possible. It follows that directed searching is not likely to be better than random searching unless navigational accuracy within centimeters is available. With the recent developments in differential GPS positioning, accuracy to within standard deviations of less than 2cm. are now claimed [6], which opens the possibility of directed searching to be accomplished with the detection sensors available.

In directed search, the area is swept a constant rate - either in spiral directions, or in a lawnmower pattern. The mean clearance rate is constant at

$$\dot{\bar{q}}(t) = U(2r)pN(\bar{n}(0)/A),$$

$$0 < \bar{n}(t)/\bar{n}(0) < 1$$

until the field is cleared. The expected time for 100% clearance is then,

$$T_o = A/\gamma(n_o, N)U(2r)pN$$

note that the time is inversely proportional to the number of robots, N, and p, the conditional probability of detection given that the target is within range of the sensor. While this performance indicates that the faster vehicle clears in shorter time, and that increasing the number of working vehicles and the detection radius has a proportional benefit, increasing N also reduces γ so that a limit exists to the benefits of increasing to number of vehicles.

TARGETED SEARCH

With the benefit of high precision navigation, it is now possible that not only could an exhaustive search be undertaken by a fleet of robots, but also, if an external means of providing targeting data (expected location of targets to be found and recovered), then, advantage may be taken of the knowledge of the terrain freeways to increase travel speed in certain paths, while slow speed search with obstacle avoidance in unknown sections will produce the knowledge necessary to map building.

At this point, not all segments of area need to be searched, and only those local areas where targets are located need to be searched. In this case, the expected clearance time is

$$T_0 = \bar{d}(UN)^{-1} + \bar{t}(p) + \bar{t}_{oa}(o)$$

in which, $\bar{t}_{oa}(o)$ is the average time spent in obstacle avoidance for n_o obstacles, $\bar{t}(p)$ is the average time spent in locally searching targets with sensor of detection probability, p and $\bar{d}$ is the average distance traveled in pickup and return of all targets.

SIMULATION AND MODELING

Operation of the robot vehicles is complicated by the fact that navigation over rough terrain is required at the same time, obstacle avoidance behaviors have to be running. Behavior based control [7] is used with the exception that arbitration between concurrently running behaviors is simplified to that of switching between discrete modes while algorithmic control laws are used to control the behaviors. An overall canonical automaton for the discrete event control of each vehicle is given in Figure 1.

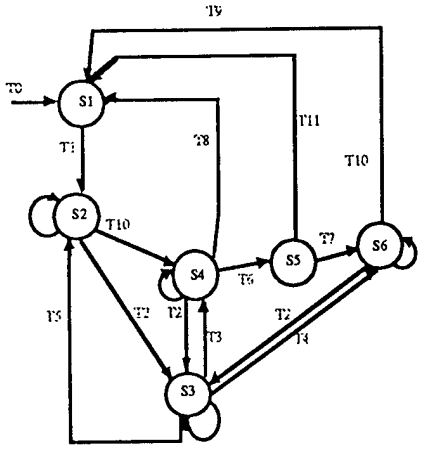
Robot Navigation

Robot navigation is accomplished with either tracked, walking and wheeled vehicles using a proportional guidance algorithm,

$$\dot{\psi}_{com}(t) = K(\psi_{com}(t) - \psi(t))$$

subject to rate limits from the actuators while the commanded heading is randomized as appropriate and given an additive bias depending on its position relative to the field

BUGS Canonical State Diagram



LIST of STATES

S1=Read_Next_Target_Location
S2=Do_Waypoint _Transit_to _Next_Target
S3=Do_Obstacle_Avoidance
S4=Do_Local_Search
S5=Perform_Pick_Up
S6=In_Transit_to_Pile

LIST OF TRANSITION SIGNALS

T0=Start
T1=Receive_Stimuli
T2=Obstacle_Detected
T3=Obstacle_Clear&&In_Local_Area
T4=Ostacle_Clear&&In_Transit_to_Pile
T5=Obstacle_Clear && In_Waypoint_Transit
T6=Target_Identified
T7=Pick_up_Done
T8=Time_Out_Searching_Exceeded
T9=Dropped_On _Pile
T10=At_Target_Area
T11=Time_exceeded_Pick_Up

Figure 1 Canonical State Diagram for Robot Mission Control

boundaries. (In practice, an electronic fence could be place around the field boundary, or if a navigation system were available, its position data could be used to set the bias).

$$\psi_{com}(t) = \psi_{bias} + \psi_{random}(t)$$

Wheel speed commands (or tracked vehicle track speeds are derived from the inverse kinematic model of vehicle motion [8]. The navigation implementation requires as a minimum, a compass - preferably without time lags in response. For vehicles that can support a navigation system with DGPS and/or odometry, a guidance law can be included using one of many schemes, the simplest of which is a line of sight guidance [9].

System effectiveness results using a "C" coded program have supplemented a concurrent graphics based simulator development, and now allow for large numbers of Monte Carlo simulations to be conducted in short times.

Obstacle Avoidance Behavior

Obstacle avoidance has been simulated with different algorithms and the simplest has been to stop upon detecion, backup turn right,go forward and check again. THis tends to get trapped in complex obstacles but the forward sector avoidance shown in Figure 2 appears to execute quickly and is robust to trapping.

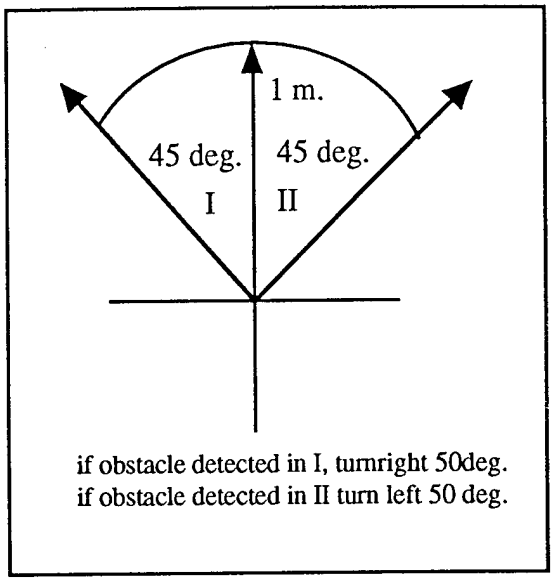


Figure 2 Obstacle Avoidance Scheme Using Forward Looking Sectors

Target Detection and Pickup

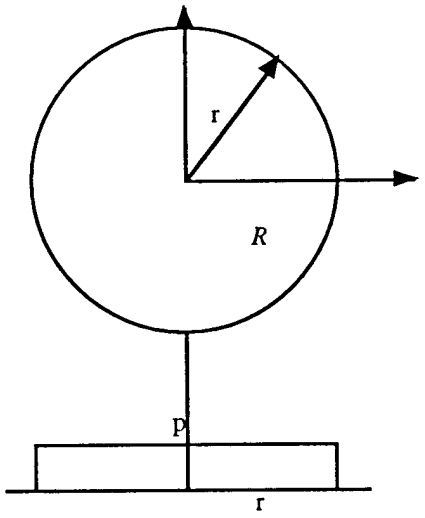


Figure 3 Uniform Target Detection Probability Density Distribution

A successful pick up is assumed if the vehicle can position itself such that the target (x_1, y_2) actually lies within R, the detection circle of radius r.

Since no sensor can be guaranteed to always give a correct signal, the conditional probability, $p(r) < 1$, is applied to determine if, given that a target lies inside the region R with the nominal detection radius r from any vehicle, a detect signal is given.

$p\,(r)$ is an appropriate function of radial displacement, although the "cookie cutter" model has been used in this work to date. More representative distributions are easily implemented. A detection signal is declared positive if a uniformly distributed random number, r_n : [0,1] is such that $r_n < p$.

In simulation, if the detection test is invoked each time where (x_1,y_2) lies in R, the effect of multiple applications distorts the apparent success rate. To eliminate this distortion, the test is applied once only after the region R is reached. A perfect pickup has been assumed for these results.

RESULTS

In a scenario that models a uniformly distributed UXO field 60m square, with 72 targets and a similar number of uniformly distributed obstacles, mean and standard deviation of clearance times are found from up to 80 simulations for each particular case. The number 80 was selected based on convergence of the statistics to an invariant result.

In general, the results follow the theoretical exponential clearance performance. Figure 4 indicates a typical path segment, and figure 5 , the improvement obtained by the use of multiples of vehicles in the same area performing clearance. The results in Figure 5 includes obstacle avoidance and returns to a single pile point in the center of the field.

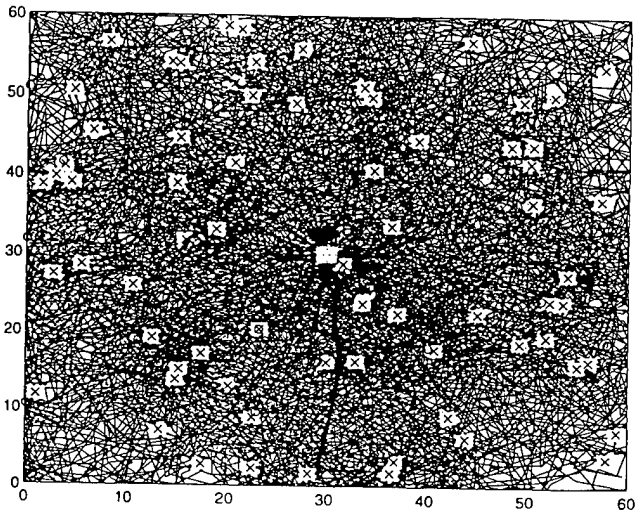


Figure 4 Typical Random Paths For 10 Robots. O Are Targets, + Are Obstacles.

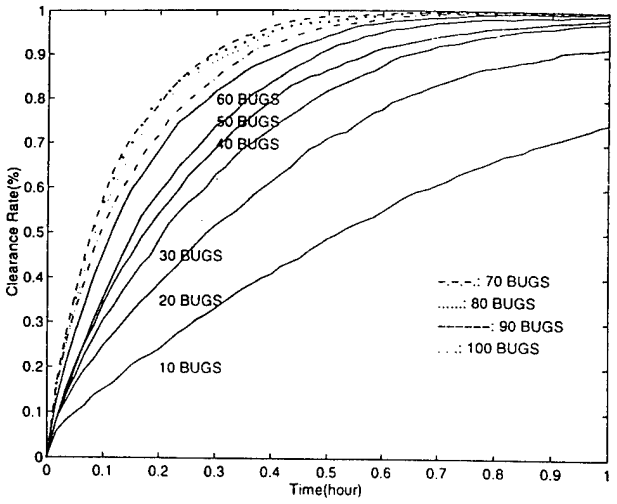


Figure 5 Clearance Performance In Percentage Cleared Versus Time (Hours), [60*60 M Area With 72 Targets And 72 Obstacles, Uniformly Randomly Distributed, Robots With 1m. Detection Radius Traveling At 0.2 M / Sec.], (Electronic Fence Gives Signals To Reflect The Path To The Interior).

It is apparent from Figure 5 that there is a number of robots beyond which further increase of rate is limited. The reason for this lies in the fact that while increasing N reduced the characteristic clearance time, increasing N also reduces $\gamma(n,N)$ and the effective speed of transit because of increased obstacle avoidance operations.

Sensor Imperfection

The effect of using imperfect sensors for the detection of

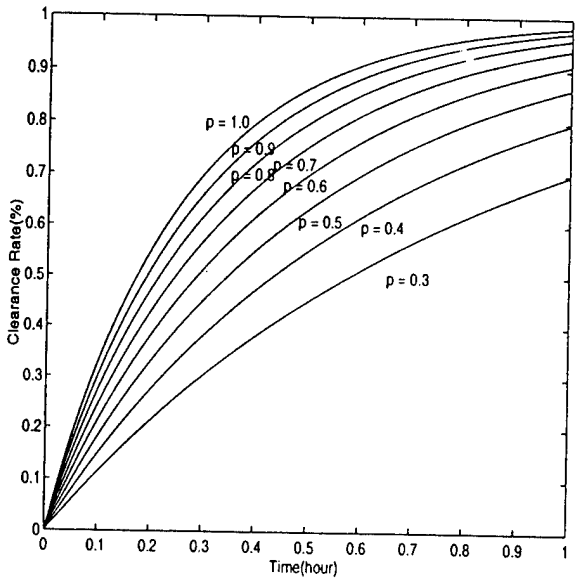


Figure 6 Effect of Detection Sensor Imperfection, 10 Robots, Same Scenario, Without Obstacles

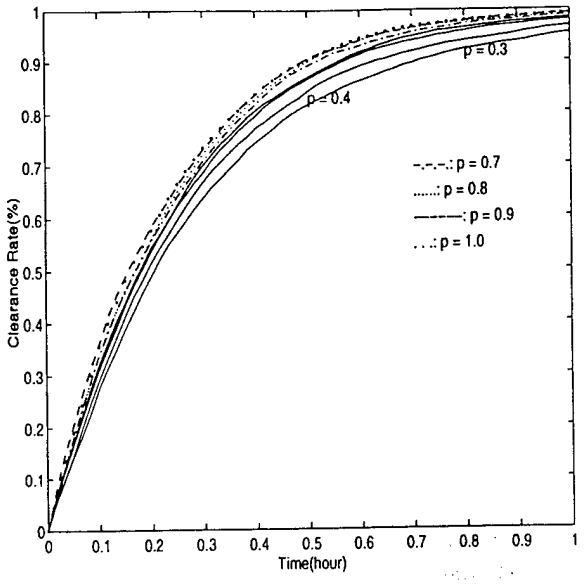


Figure 7 Effect of Detection Sensor Imperfection, 50 Robots, Same Scenario, Without Obstacles

munitions is illustrated in Figure 6, where for random search, the characteristic clearance time is increased since multiple "looks" at any one target are required to declare detection.

Obstacle Avoidance Delays

In a field cluttered with obstacles, the obstacle avoidance maneuvering consumes extra time. Indeed, with a large number of robots also in the field obstacle avoidance on

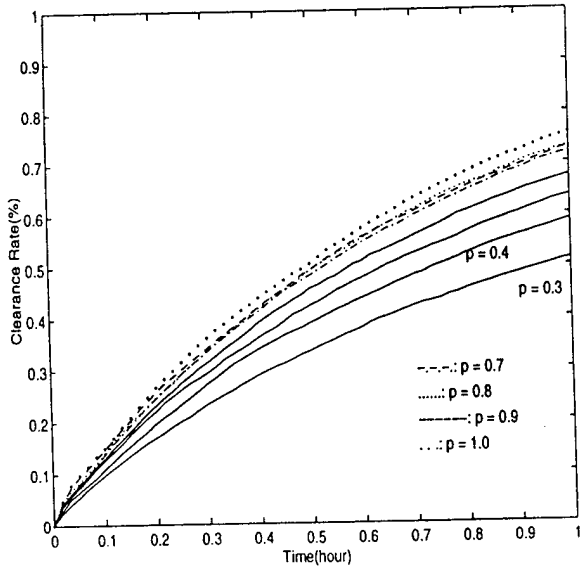


Figure 8 Influence of Imperfect Detection Together With Obstacle Avoidance - 10 Robots

other robots as well as obstacles reduces the clearance performance to the point where no further improvement is found if the density of robots is approximately equal to the density of targets. Figure 8 with obstacles, versus Figure 6 without, shows that, in this case where the density of obstacles is also equal to the density of targets, the characteristic rate is approximately one half of that without obstacles for the same number of robots.

Probability of Casualties

When using robots to pick up UXO pieces, handling qualities are not likely to be as careful as with human hands and one piece of information is the expected loss of robots in the field. This problem has been simulated under the assumption that once a detection has been registered, there will be a separately applied probability (0.2) that the robot will be destroyed. Additionally, if the robot does not detect a target within its region, R, there is also a 0.2 probability that it will be lost to unplanned contact with the munitions. Both of these cases contribute to a loss of robots. Results for the same scenario as simulated above give the following losses.

TABLE I
Mean Robot Losses From UXO Pick Up With Varying, P
0.2 Probability of Explosion Upon Pickup

P	10 Robots	20 Robots	30 Robots	40 Robots	50 Robots
1.0	8.73	12.85	14.24	14.39	14.93
0.9	8.99	12.90	14.55	13.70	14.88
0.8	8.60	13.75	15.01	14.85	14.90
0.7	8.80	13.44	14.89	14.63	15.16
0.6	8.44	13.86	14.74	15.06	15.40
0.5	8.64	13.48	14.91	16.36	14.98
0.4	8.45	13.28	15.05	15.73	15.76
0.3	8.09	13.14	15.49	16.38	17.16

While there are many statistical issues in the above, these results represent the mean losses taken over 80 simulations for each case and appear to generally conform to the idea that 20 percent of the robots are lost. The result is not unexpected, however, further work needs to be done to determine what a probability of detonation would be for each target type, and how the design and control of the pickup mechanism would be able to reduce it.

CONCLUSIONS

Studies to date indicate that clearance performance can be potentially better than currently obtained by EOD teams at the same time as provision of extra safety. Vehicle speeds must be at least 20 cm/sec in search, and higher in transit through known clear paths would be desirable. Improvements in munitions detection sensors are constantly being sought, and provided that the vehicle systems being developed can be made at very low cost, robot clearance

systems could become a reality. Much more experimental work is needed.

ACKNOWLEDGMENTS

The authors wish to recognize the financial support of the NAVEODTECHDIV, Indian Head, MD., and the technical input of Dr. Gage from NRad, San Diego, as well as the valuable technical discussions with Foster Miller(Arnis Mangolds), Draper Laboratories(David Kang) and I.S Robotics(Joe Jones), Cambridge, MA.

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Unexploded Ordnance Clearance and Minefield Countermeasures by Multi-Agent, Small Robotics

Craig Freed and Tuan Nguyen
Naval EOD Technology Center, R&D Dept.

The Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) is developing small robotics for the clearance of ICMs (Improved Conventional Munitions) and the clearance of land mines. We call the project BUGS (Basic Unexploded Ordnance Gathering System). These vehicles will be cheap and easy to use. The BUG vehicle will autonomously go into an area where there are dud submunitions and pick up the submunition and carry it to a collection point. A countermeasure is being developed to use the same small robotics to drive into a mine field and place explosive charges on top of mines. The NAVEODTECHDIV concept development has been based on a simple and inexpensive subsumptive/ centralized control architecture to perform complicated tasks. A skid steered wheeled platform with few simple sensors has been fabricated and shown to operate autonomously to perform the UXO and MCM tasks. Only prelaunch commands are needed for autonomous operatoins by a controller with low computational abilities.

Because a full paper was not received by publication date, the above Abstract appears in this Proceedings. The authors can be reached at NAVEODTECHDIV, 2008 Stump Neck Road, Indian Head, MD 20640; telephone 301-743-6850, X 281.



Basic Unexploded Ordnance Gathering System

Craig Freed

20 November 1996

BUGS

- Overview
  - Goal
  - Mission
  - Background
  - Approach
  - System
  - Technologies

BUGS



Goal

- *Develop Technology Enablement Areas Related to the Use of Small Robotics and Identify Critical Technology Issues*
- *Develop Multiple, Small, Inexpensive, Autonomous Robotic Agents to Clear Small Unexploded Explosive Ordnance and Neutralize Land Based Mines*
- *Perform Pick-Up or Blow-In-Place Operations*
- *System Operable Over a Wide Variety of Terrain/Conditions*

BUGS

- *EOD Problem*
  - *Improved Conventional Munitions*
  - *Scatterable Submunitions*
- *USMC Problem*
  - *Surface/Subsurface Anti-tank Mines*

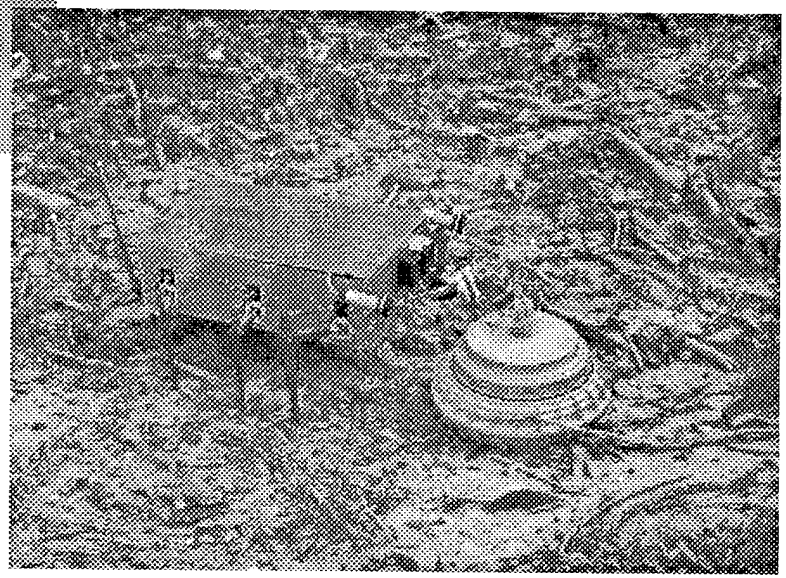
BUGS

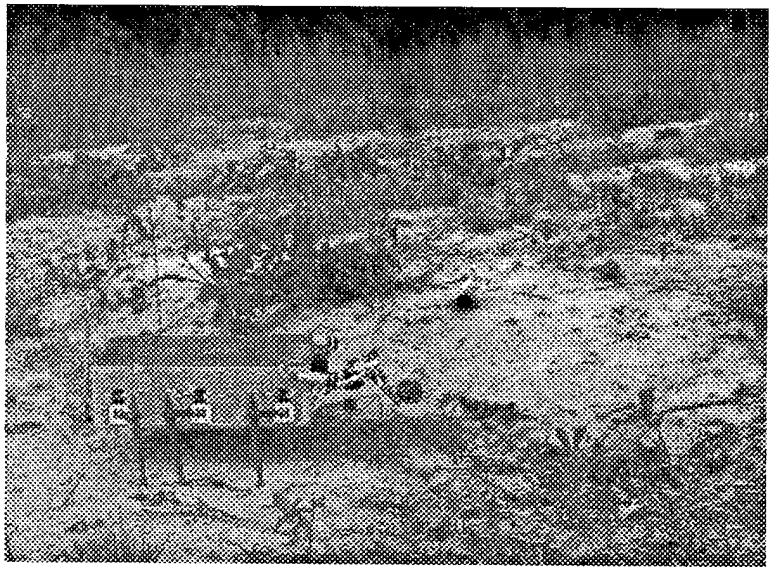
- Background
  - Formulated Concept
    - User Input and Field Visits
    - Threat Assessment
    - Technology Assessment
  - Leveraging
    - ARPA, NASA, ONR, OSD-JRP, NCCOSC, MIT, USMC, NPS
  - Proof of Concept Testing
    - BUG Off, 31 July 1996

BUGS

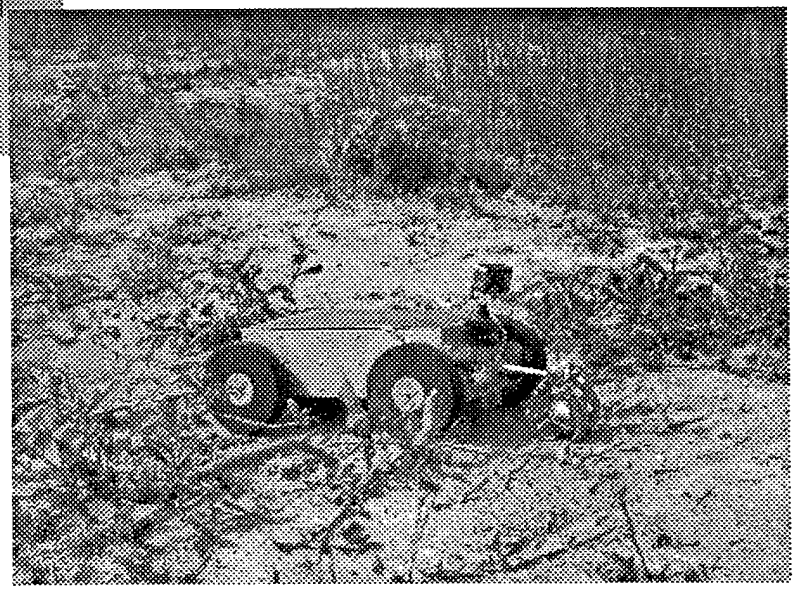
- *Approach*
  - *Develop Vehicle Control Logic*
  - *Develop Test Bed Vehicles*
  - *Develop Manipulator*
  - *Integrate Reacquisition Sensor*
  - *Integrate Neutralization Charge*

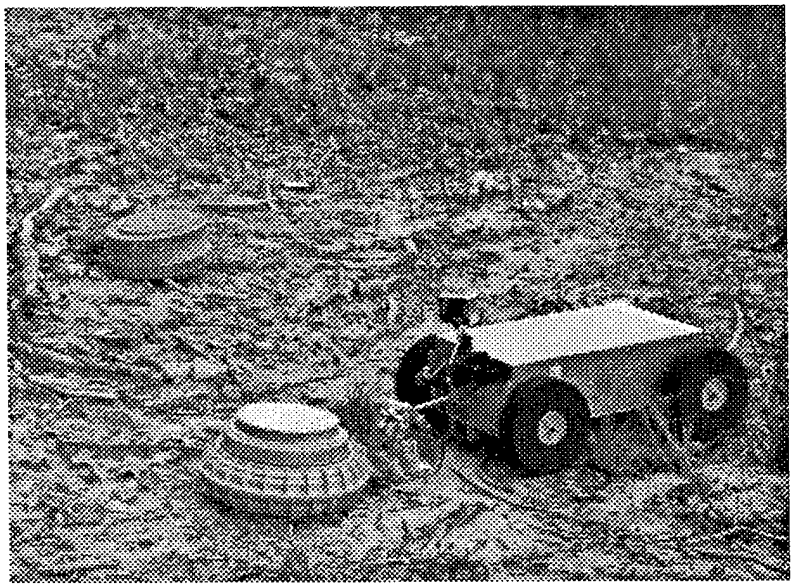
BUGS





BUGS





BUGS



- *System*
  - *Random Search*
  - *Bounded Search*
  - *Directed Search*
  - *Two Vehicle Concept*
  - *Clearance Time*
  - *Model Based Simulation*

BUGS

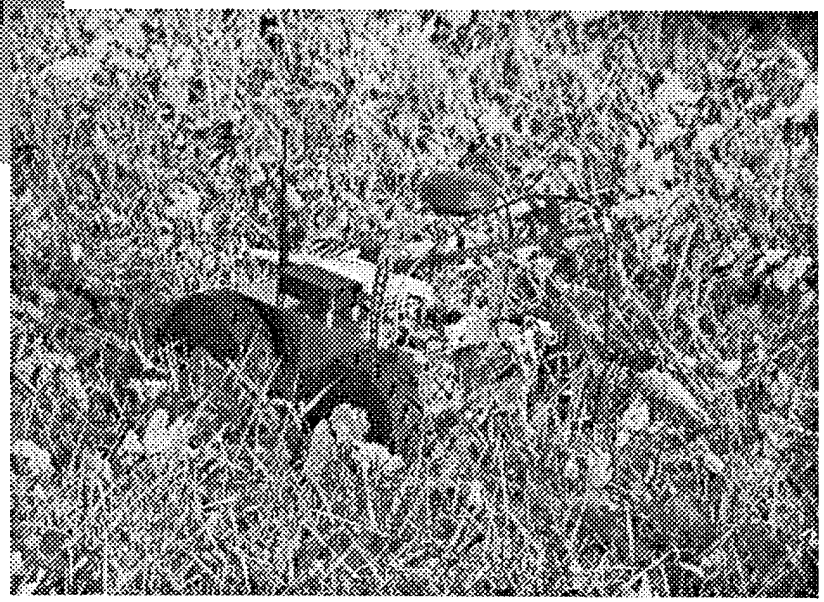
- System
  - Reconnaissance Platform
    - High End Sensors, Multi Sensors
    - Autonomous Patterned Search
    - Navigation/Marking Network
    - Provide Location/Classification to BUG
    - EOD Tech./ Combat Engineer
    - AutoRECORM, COBRA, ASTAMIDS

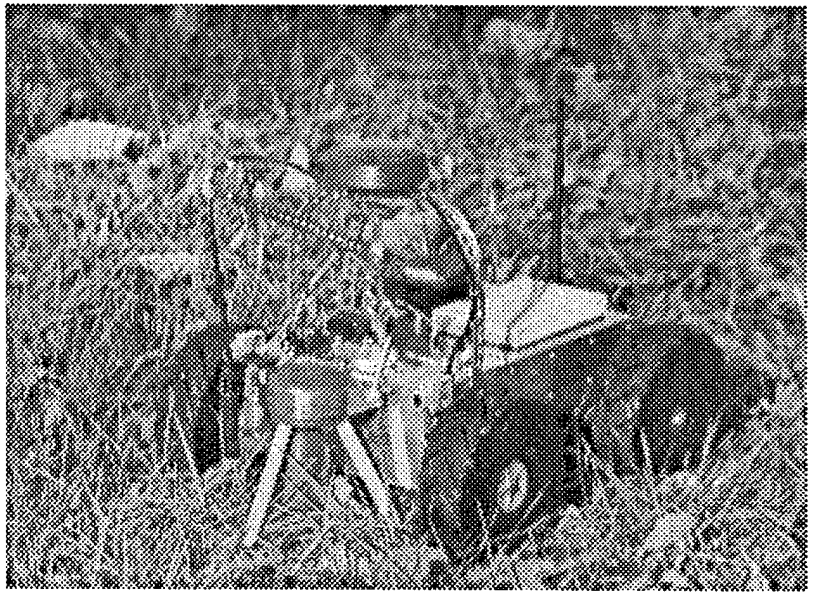
BUGS



- *System*
  - *Basic UXO Gatherer (BUG)*
    - *Simple Reacquisition Sensor*
    - *Simple Navigation*
    - *Perform PUCA/BIP Mission*

BUGS





BUGS



- *Propulsion*
  - *Platform: Wheeled (14"x8.5"x4.25")*
  - *Velocity: 2.5 ft/sec*
  - *Operational Duration: 1.5 hr*
  - *Motors: 12 VDC with Shaft Encoder*
  - *Wheels: Foam Rubber*
  - *Steering: Skid*
  - *Weight: 19 lb*

BUGS



- *Navigation*
  - *DGPS: 2cm, Premier*
  - *Dead Reckoning:*
    - *Electronic Compass, Precision Navigation*
    - *Shaft Encoders, Micro Mo*

BUGS



- *Sensors:*
  - *Obstacle Avoidance*
    - *IR Beam*
  - *Target Detection*
    - *Inductive*

BUGS

- *Manipulation:*
  - *Jaws - PUCA*
  - *Release - BIP*
- *Control:*
  - *NAVEODTECHDIV Subsumptive/Centralized*
  - *Tele-Operations - Video & Remote Commands*

BUGS



- *Vehicle Command Inputs:*
  - *Prelaunch Commands*
    - *Start Point*
    - *Way Points*
    - *Target Locations and Types*
    - *Drop Point*
  - *Remote Commands*
    - *Left, Right Forward, Backward*
    - *Start, Stop*
    - *Pick-up, Drop*

BUGS



- *On-Board Processing*
  - *Stores Mission Plan*
  - *Executes Mission Steps*
  - *Behavior Arbitrator*
  - *Obstacle Avoidance*
  - *Sensor Input*
  - *Manipulation Control*
  - *Mobility Motor Control*

DARPA's Autonomous Minehunting And Mapping Technologies (AMMT) Program

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Abstract -- The C. S. Draper Laboratory, Inc. (Draper) recently completed the at-sea test phase of the Autonomous Minehunting and Mapping Technologies (AMMT) Program for the Defense Advanced Research Projects Agency (DARPA). The primary objective of this program is to develop and demonstrate advanced minehunting technologies that will enable Unmanned Undersea Vehicles (UUVs) to clandestinely survey an undersea area for mines and collect data for post mission mapping of the surveyed area. The survey data must be of sufficient quality to support selection of an amphibious operating area and subsequent neutralization of mine or obstacle threats.

As integration contractor for the AMMT Program, Draper modified one of DARPA's existing UUVs; which was previously designed and built by Draper, and used for DARPA's Mine Search System Program. State-of-the-art technologies in the areas of Sonar Mapping, Navigation, Acoustic Communications, Imaging, and Mission Planning were incorporated into the AMMT vehicle, resulting in a system having the capability to perform an autonomous survey and meet program objectives. The vehicle was subsequently tested at-sea to demonstrate the advanced minehunting technologies and concepts.

This paper describes the develop-ment and integration of technologies required to perform the clandestine AMMT mission. Details of the autonomous adaptive mission planner and the execution of the at-sea tests are presented.

I. BACKGROUND

C.S. Draper Laboratory, Inc. (Draper) has been developing Autonomous Undersea Vehicles (AUVs) and associated vehicle subsystem technologies for the Defense Advanced Research Projects Agency (DARPA) for several years. The DARPA Unmanned Undersea Vehicle (UUV) Program began in May, 1988 when Draper was contracted to design, fabricate, assemble, test and deliver two UUVs. The goal of the joint DARPA/Navy UUV Program was to demonstrate that UUVs could meet specific Navy mission requirements with emphasis on the use of state-of-the-art technology and "rapid prototyping" of hardware. Rapid prototyping of UUV systems and subsequent at-sea test demonstrations of Navy mission concepts would allow the Navy to determine whether the concept should be taken to full scale development.

The first UUV was delivered for at-sea testing 19 months after the start of the contract, and underwent preliminary performance testing and evaluation. Since these initial sea trials, the vehicles have been modified and configured to validate several Navy operational missions. The first mission to be validated was the Tactical Acoustic System (TAS), which was a classified mission and will not be discussed. The second mission demonstrated high data rate underwater laser communications between an AUV and a manned submarine. The third mission was the Mine Search System (MSS), which used a fiberoptic or acoustic data link and demonstrated that a UUV could guide a surface ship or submarine through a minefield in a semi-autonomous mode. In a fully autonomous mode, the MSS vehicle performed a survey of an area and subsequently transferred mine target data from the surveyed area to a host via radio from a rendezvous point.

In recent years, DARPA has responded to the priority need for mine countermeasures clandestine reconnaissance with the Autonomous Minehunting and Mapping Technologies (AMMT) Program. The AMMT Program is a follow-on effort to DARPA's MSS Program and builds significantly upon MSS achievements in five technology areas: Sonar Mapping, Inertial Navigation, Acoustic Communications, Undersea Imaging, and Mission Planning. These minehunting technologies were integrated into a modified MSS vehicle and underwent a five month at-sea test program, which concluded in May of this year. The intent of the AMMT Program is to demonstrate the successful integration of these minehunting technologies into an autonomous vehicle, and in so doing gain insight and information which will prove beneficial to the Navy's present off-board sensor programs; the Near Term Mine Reconnaissance System (NMRS) and Long Term Mine Reconnaissance System (LMRS), and also support other Navy UUV Program priorities.

II. Goals and Objectives

The AMMT Program has four major objectives in demonstrating is effectiveness as a mine countermeasures systems:

- Develop and demonstrate comp-lementary technologies that will enable an autonomous UUV to clandestinely survey an undersea area and collect data for post mission mapping of the surveyed area
- Provide data products of sufficient quality to support selection of an amphibious operating area and subsequent neutralization of mine or obstacle threats
- Transmit, in near real time to a host, mission maps and images of targets identified as having a high probability of being mines
- Provide a post-mission map of the surveyed area

In meeting the overall program objectives, a test program was developed to demonstrate and validate advanced vehicle technologies for the following:

- Mine detection and classification
- Precise mine and obstacle localization
- Optical Imaging of underwater objects
- Acoustic communication of mine/ obstacle images to the surface for near real-time identification
- Mapping bottom topography with locations of mine/obstacles
- On-line mission planning

In order to meet program objectives and perform the technology demonstrations, there were four program requirements, generated early in the program. These requirements were successfully met during the course of the program and are as follows:

- Provide a reliable, fault tolerant integrated testbed vehicle
- Develop a support equipment suite
- Provide the capability to launch, recover, perform diagnostic tow, and maintain/service the vehicle
- Select a test site and mobilize for conduct of the at-sea test program

III. System Development

A. Participants

Draper Laboratory was the system design and integration contractor for the AMMT Program. Responsibility included modeling the GFE (Government Furnished Equipment) UUV, integrating the ahead looking sonar and mapping system (GFE), the laser line scan imaging system, the inertial navigation system, and the acoustic modem system into the vehicle. Draper also provided the adaptive on-line mission planner.

As system integrator, Draper supplied the AMMT Test Director who formulated and executed the Test Plan.

Applied Research Laboratory, University of Texas (ARL:UT) was the designer and builder of the ahead looking sonar and mapping system and associated monitoring and control support stations.

Lockheed Martin Tactical Defense System (LMTDS), through its Loral Defense Systems-East, supplied the inertial navigation system which incorporated an inertial measuring unit (ring laser gyro), doppler velocity measuring sonar log, conductivity-temperature-pressure/depth sensor, and appropriate software resulting in a high accuracy navigation system.

Woods Hole Oceanographic Institution (WHOI) supplied the acoustic modem that would transmit and receive acoustic data, and have the capability to compress laser line scan images for accelerated acoustic transmission.

Raytheon supplied the Laser Line Scan System (LLSS). This system would be used to image targets as directed by the vehicle's mission planner.

Naval Surface Warfare Center, Carderock Division, Ft. Lauderdale Detachment (NSWC) was selected as the test support contractor for the conduct of the AMMT at-sea tests. They supplied shore facilities with associated technical and security and the support ship, M/V SeaCon.

Johns Hopkins University / Applied Physics Laboratory (JHU/APL) supplied Requirements and Data Analysis support and the co-Test Director for the at-sea tests.

Vail, and previously PRC provided support to DARPA's Tactical Technology Office. Fig. 1 depicts the program organization and participants.

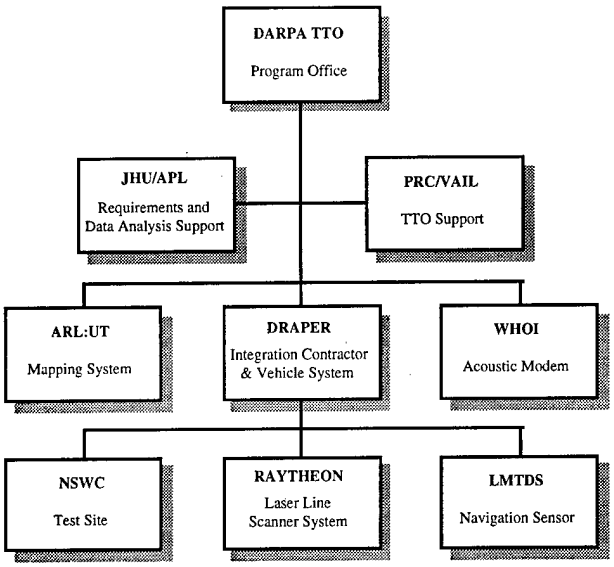


Fig. 1. AMMT Test Organization.

B. Vehicle Systems

The AMMT vehicle, as shown in Fig. 2, is a modified version of the MSS vehicle. The 1.1 m diameter hull was extended to an overall length of 12.5 m, by the addition of a new 0.7m titanium hull insert. The additional insert volume houses two mapping processors for the sonar subsystem. The basic MSS vehicle and control system remain intact along with the Ahead Looking Sonar System. Mechanical mounts were added to the bow of the vehicle to allow a bridle to be used for vehicle towing, and to provide for attachment of a tow cable for submerged sonar diagnostic towing. A GPS system is integrated into the vehicle with the antenna added to the vehicle's 1.1 m erectable mast, also used for the radio antenna. The acoustic modem's two projectors are installed in the vehicle's aft free-flood section. The modem's eight receivers are mounted in the vehicle's forward free-flood section and the modem's computer is installed in the vehicle's electronic section. The Doppler aided-inertial navigation system components include a broadband Doppler Sonar, located in the forward free flood area, and an inertial reference unit, navigation computer and recorder located in the vehicle's payload section. Power to the various subsystems is distributed from the vehicle's 300 Kw-Hr silver-zinc battery. In the AMMT configuration the vehicle is capable of diving to 460 m, and achieving speeds of 2-7 knots.

The mapping sonar utilizes the MSS Ahead Looking Sonar and performs additional functions of bathymetric mapping and precise navigation. Computer aided detection enhancements were added to the sonar data processing, which also generates bottom relief profile maps. A byproduct of the mapping process is the ability to improve vehicle navigation using sonar data. The Acoustic Tracking and Navigation (ATN) function of the mapping sonar, which estimates vehicle position based on ping-to-ping correlation and tracking of bottom features, provides input to the vehicle's navigation filter for integration with the navigation estimates from the inertial navigation system.

Acoustic communications at rates to 10 kbps over ranges up to 10 km were goals for the program. The acoustic communications system also had the additional function of image management. Prior to transmission of the laser line scanner images and sonar maps topside, images and map data were compressed to reduce transmission time. Subsequent decompression and enhancement of the transmissions was provided in the host communications support equipment.

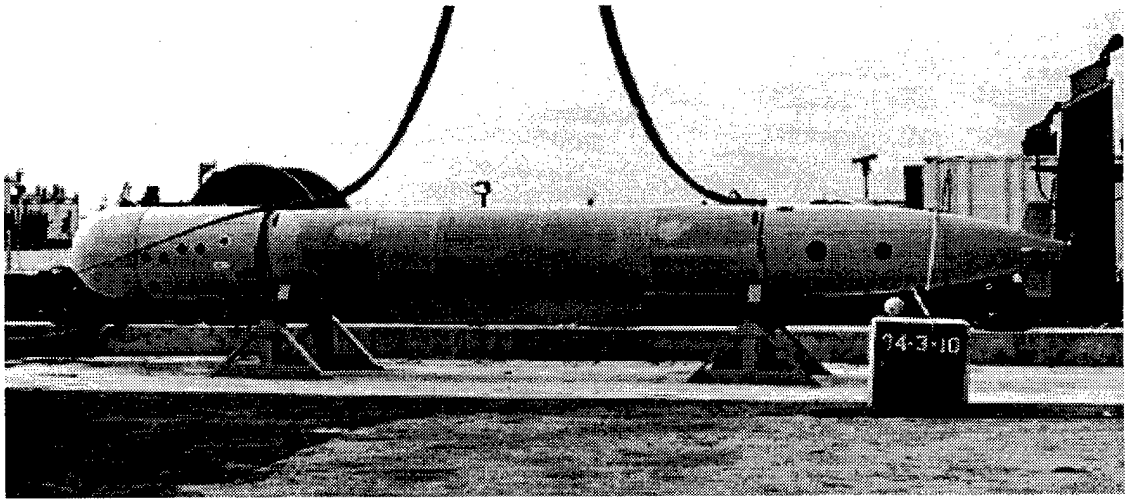


Fig. 2 AMMT Vehicle.

The primary imaging system on the AMMT vehicle is a Laser Line Scanner System (LLSS) provided by Raytheon. The system uses a 400 mw laser and has the ability to provide sampling resolutions of 512, 1024, 2048, and 4096 pixels over a 70° field of view with 14 bit amplitude resolution. The laser sensor is mounted to the underside of the vehicle hull in a faired, fiberglass pod. For the AMMT Program application, the LLSS was designed to provide high resolution images at altitudes of 11.3 - 14.0 m over the target at speeds up to 6 knots. Because the LLSS had not been previously used in autonomous operations and to mitigate the potential risk that the system might not operate satisfactorily in the vehicle, a second imaging system was integrated into the vehicle. The backup system utilizes an electronic still camera and strobe lights, which were mounted in the aft and forward freeflood sections of the vehicle respectively.

C. Vehicle Mission Planner

Early DARPA UUVs guidance and control system required operators to specify a pre-planned sequence of guidance commands to control vehicle trajectories. This capability has proven to be very reliable and robust and yet limited relative to contigent maneuvers. To be a truly autonomous system, the vehicle must be able to execute obstacle avoidance, terrain following, conditional target imaging, and optional path planning in real-time as well as simple high level specification of mission objectives and constraints. The on line mission planner achieves this goal via real-time assessment and trajectory planning and interfaces with the UUV guidance and control system.

Planning is a search through the infinite space of possible decisions to find that sequence of decisions, or plan, that best achieves the given objective. A search algorithm generates possible vehicle trajectories which are then scored using a cost function. The cost function is a weighted combination of the estimated resources (time and fuel) needed to perform each activity in the mission and the estimated value of each mission objective. The value of an objective is specified by the user and is relative to other activities in the list. If an activity is twice as important to complete as another activity, then its value would be twice as much as the other. The mission planner scales this value by the probability of completing the objective in the mission. In this manner, a near optimal vehicle trajectory is selected given the specified goals and constraints.

Examples of mission planning capabilities are presented in Figures 3 and 4. Both include surveys where the lane growth was North - South (North on tope of page). Fig. 3 shows the planned and actual path for a 150 foot lane spaced survey. For planning purposes, the vehicle's turn diameter was limited to 500 feet. The planner generated detailed maneuvers based on constant diameter turns while accom-

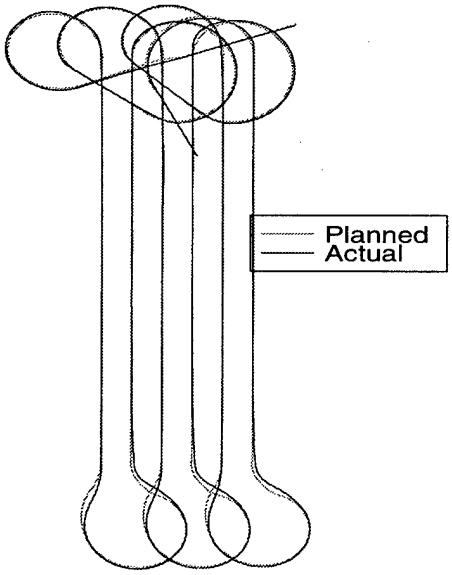


Fig. 3. Actual Path (dark) vs. Desired Path (light).

-modating ocean current. Note the effects of varying ocean current on the shape of the northerly and southerly turns.

Fig. 4 shows the actual groundtrack for a survey, imaging and depth excursion mission overlaid on the pre-mission input display. After launch, the vehicle went to the start point, conducted a survey over the desired region while avoiding known obstacles, performed imaging maneuvers, sampled the water column with a depth excursion and finally ended the mission at the desired waypoint. The survey region

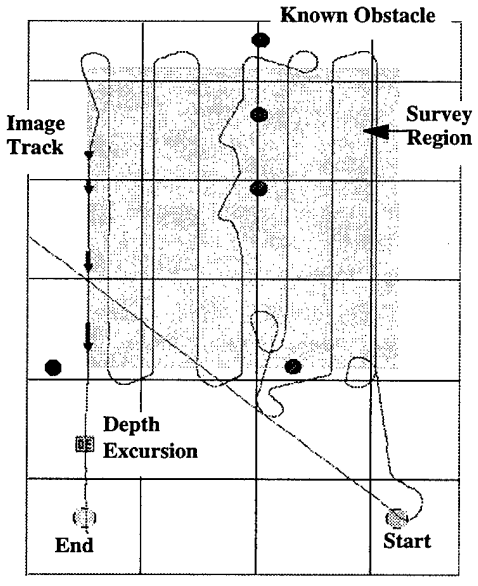


Fig. 4. Mission Groundtrack Over Pre-Mission Plan.

was well covered and all obstacles were avoided. The additional maneuvers or loops in the groundtrack occurred because the planner was trying to attain the proper vehicle heading at the desired location. These maneuvers are an artifact of how the planning problem was decomposed. For instance, if the planning time horizon were longer, there would be no need for additional maneuvers.

D. Schedule and Milestones

The AMMT Program originally began in April 1993, as a follow-on effort to DARPA's MSS Program. The program was stopped in October 1993, due to a congressional delay in GFY 1994 funding, and restarted in July 1994. Following in-laboratory systems integration, mobilization for the program's at-sea test phase at NSWC's South Florida Testing Facility began in December 1995. The at-sea test phase of the program occurred over a five month period ending with demobilization of the test site in mid-May 1996. During the test program, many of the subsystem test demonstration milestones were successfully met. However, full mission demonstrations of the integrated AMMT system were not completed due to program schedule and cost considerations.

IV. System Test Preparations

A. Test and Support Facilities

Potential test sites were identified from the Pacific Northwest (Nanoose and Dabob) to San Diego to New England waters to Florida.

The Naval Surface Warfare Center's South Florida Testing Facility was selected as the site for the AMMT Program's at-sea tests and mission demonstrations. Located in the Ft. Lauderdale area of Florida, the facility was selected for its proximity to the open ocean, and the suitable bottom features and water depths available in it's test area. The size, availability, and launch/recovery capability of NSWC's support ship, M/V SeaCon, was also a major reason for selection of the test site. The site is located on the Port Everglades channel and permits rapid access to the open ocean without the penalty of a long surface transit. The M/V SeaCon is equipped with a 22 ton crane which is capable of lifting the AMMT vehicle for launch and recovery operations and a winch capable of supporting vehicle diagnostic tow operations. The M/V SeaCon is also large enough to permit the AMMT Control Van, a standard 40 foot ISO container, to be mounted on its deck along with pedestals for vehicle support during transits to and from the test area. The Control Van housed the control and tracking equipment to support the AMMT vehicle and was the central monitoring location for vehicle performance and data collection. The SeaCon also housed and deployed the V-Fin assembly which carried the topside (host) acoustic modem's array, amplifier, and projector.

In addition to the equipment mounted on the M/V SeaCon, a temporary shelter was constructed dockside to house the vehicle during assembly, disassembly, maintenance, repair, and battery charging. The vehicle was rolled out of the shelter on its handling carts and then shore-craned onto a set of support cradles dockside where the LLSS pod was mounted to the vehicle. The vehicle was then either crane launched or transferred to the pedestals on the SeaCon for travel to the test site and launch at-sea. Fig. 5 shows the vehicle in the maintenance shelter on it's handling carts.

In the water, the vehicle was handled with the use of inflatable support craft, including a pontoon type inflatable boat developed by Draper, to control the vehicle during surface tow operations. The vehicle could be surface towed from the dock to the test site using the pontoon boat; or carried to the test site on the pedestals onboard the SeaCon, and craned into the water, sea-state permitting. The vehicle was able to be handled using the pontoon boat in seas to sea-state 3, and launched/recovered using the support ship crane in sea-states of 1 or less. Generally, the vehicle was towed either to or from dockside using the pontoon boat. After being towed dockside, the vehicle was lifted to the pedestals on the support ship using the support ship crane for subsequent transfer to the shore cradles. Fig. 6 shows the vehicle in the water with the pontoon boat.

An exercise minefield was installed in the off-shore test area, to provide targets for the Ahead Looking Sonar. Approximately 40 bottom and moored test mines were deployed in water depths ranging from 46-180 m. A pattern of mine lines parallel to the shore was used to represent a mine barrier which might be used to deter an amphibious assault from the sea. Special optical targets were also placed on the ocean to evaluate the dimensional and constrast resolution of the vehicle's imaging systems.

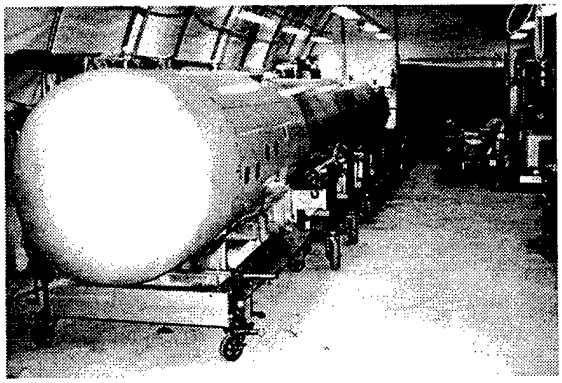


Fig. 5. UUV in Maintenance Shelter.

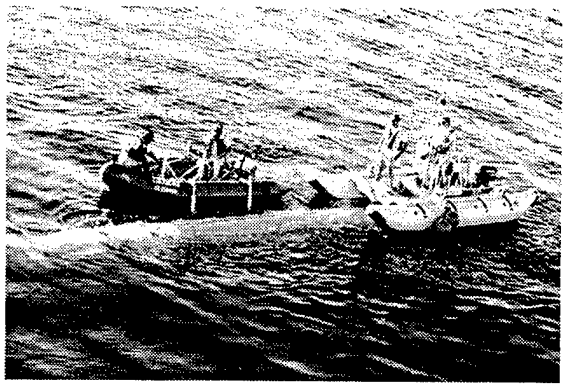


Fig. 6. UUV and Pontoon Boat.

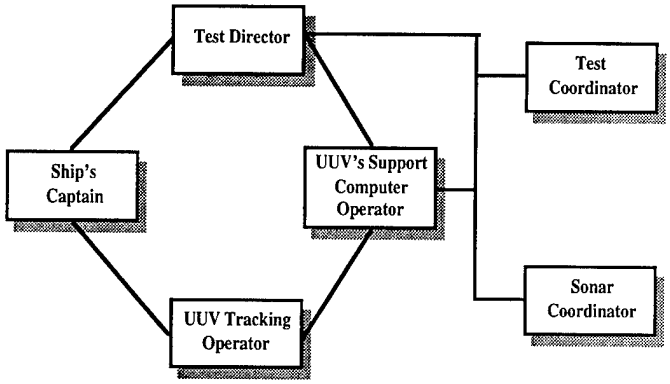


Fig. 7. Command and Control Organization

Draper's simulation facility provided support to the program during laboratory vehicle integration and at-sea testing. All vehicle software, including the mission planner, was run in the high fidelity hybrid simulation for verification and validation. Mission software for each individual test day was verified in the simulation facility before its use at-sea. In addition, the facility was used to troubleshoot and resolve the problems and anomalies, encountered during at-sea testing, by recreating the actual test conditions in simulation and running the tactical software.

B. Test Plan Formulation

A very large effort was expended to formulate the AMMT At-Sea Master Test Plan. Once the objectives were finalized, the proper sequence of events could be established, test organizations created, program requirements identified and executed, and Master Test Plan designed.

Support Groups

The Test Working Group (TWG) consisted of the major system suppliers identified in the Test Organization. This group had the responsibility to provide coordination in the planning of the test program. The Chairman of the TWG was the AMMT Test Director. Meeting's were scheduled as necessary to ensure that all test requirements were evaluated and/or incorporated during engineering design review phases and test plan development. The TWG was replaced by the Joint Test Group (JTG) at the start of the at-sea testing.

The JTG had the responsibility for overseeing the conduct of the at-sea test program. They operated as the day-to-day guidance, review, approval, and on-scene authority for at-sea operation. The head of the JTG was the Test Director.

Command and Control Organizations

The AMMT command and control organization is presented in Fig. 7.

The Test Director is responsible for the conduct of the at-sea tests. He is supported by:

1) Ship's Captain: Responsible for all support ship activities, including safety and emergency response. Also, ship's crew will be responsible for UUV handling and associated ship maneuvering activities.

2) Test Coordinator: Every at-sea event has a test coordinator who is responsible for the conduct and execution of the specific event.

3) UUV Tracking Coordinator: Maintains range and bearing of UUV relative to the support platform. Recommend maneuver for optimal system monitoring.

4) UUV Support Computer Operator: Conduct pre-launch and post-recovery checkout of UUV and payload. During test, vehicle will be queried for status and subsequent interrogation of vehicle fault status. During operations, operator can download mission activity changes as directed by the Test Director.

5) Sonar Coordinator: Responsible for sonar mapping system operations, monitoring of displays, and data collection during Diagnostic Tow Testing.

C. Preliminary Requirements

The AMMT Test Program included preliminary sequential phases followed by the at-sea test and demonstration. The following tasks had to be successfully undertaken prior to the at-sea testing phase:

1) Test and Evaluation and Factory Acceptance Tests (FATs) of GFE UUV prior to delivery to test site.

2) FATs conducted on the various subsystems to be incorporated in the UUV, including the GFE mapping sonar system.

3) Testing and integration of AMMT sub-systems and stand-alone items.

4) Testing and integration of AMMT sub-systems in the UUV.

Prior to the start of the at-sea tests, a number of program requirements had to be generated to meet program goals and perform technology demonstrations.

The System Integrator had to provide a reliable fault tolerant, integrated testbed vehicle. This required the engineering of Interface Control Documents (ICDs) for each subsystem incorporated into the vehicle, and execution of the preliminary pre at-sea test tasks identified above. All program requirements were reliably met for timely commencement of the AMMT at-sea test.

Numerous support equipment suites had to be designed, built, and incorporated into the vehicle system for proper execution of the AMMT tests. The vehicles Emergence Recovery System (ERS) was augmented with an Argos beacon and an inflatable enhanced radar target buoy. During autonomous operations, the vehicle's activities and position were shown on a real-time tactical display. During pre and post test activities, methods to monitor and execute data transfer were formulated along with an external cooling system.

D. Master Test Plan

Based on objectives, requirements, system and budgetary constraints, a Master Test Plan was formatted. Each days activity was planned from start to finish and presented in a Gantt chart format. Consideration was given to maximum use of UUV battery capacity between recharging and minimizing night operation for safety reasons and weekend operation because of the very high volume of large pleasure craft traffic in the operating area. Each daily operation's Gantt chart identified the activity name, duration, start time, support ship start and end time, and daylight hours. Each test also identified: objectives, test method, test coordinator, test documentation, data products and format, data distribution, data analysis, and other test support. This information and the Gantt chart provided sufficient information for the JTG to plan and re-plan activities on-site as conditions dictated. The charts also presented the inter-relationship of activities.

The Master Test Plan also included a Safety, Search and Recovery (SSAR) Plan intended to assure a high state of safety and recovery readiness during AMMT UUV sea trials. The safety plan was intended to account for all situations ranging from normal vehicle testing conditions to these conditions where there was eminent risk of vehicle loss. The plan was a stand-alone document that permitted the Test Director to react based on specific, well defined, prevailing conditions.

The Master Test Plan identified the complete AMMT at-sea test when operating in a perfect, no-problem, no-failures world. Of course, that did not take place. The JTG reviewed each days activity based on the past and prevailing conditions and modified the next event to take place as required. Test Execution will identify the actual sequence of events.

V. Test Execution

After a Test Readiness Review (TRR) held in early January, 1996, AMMT was given the go ahead to proceed with at-sea testing. The test program consisted of a sequence of events, each built upon the other, culminating in autonomous missions of increasingly greater complexity and challenge.

The objective of the at-sea test program was to demonstrate the utility of the AMMT technologies in conducting a clandestine reconnaissance full mission profile. Specifically, the vehicle would transit some 25 nautical miles over-the-horizon, perform a minehunting and mapping survey over a broad area, review Computer Aided Detection results, then revisit - for imaging purposes - the more mine-like of the detected objects. After imaging with the laser, a full resolution image would be stored for post-mission retrieval while a second copy was compressed for immediate transfer by the acoustic modem to the support ship along with mapping products. A key assumption of this operational scenario and throughout the test program was that the vehicle had no prior knowledge of its environment; it would have to rely upon the ahead looking sonar to provide real-time input to the mission planner for such critical functions as obstacle avoidance and terrain following at low altitudes for imaging.

A. Preliminary Tests

Vehicle handling equipment and procedures were first verified with a mock-up or dummy vehicle. Then came handling of the actual vehicle. A specially designed inflatable catamaran could safely fasten itself to the bow of the vehicle and still employ an outboard motor for local maneuvering and control. The crews of the highly versatile support craft handled a number of chores such as attaching and removing liftings slings from the crane and removing the surface tow bridle upon arrival at the dive point.

A deep berth on the Intracoastal Waterway was utilized for calibration of doppler sonar bias parameters and for acoustic interference tests. Draper Lab, as system integrator, developed a Ping Management technique to ensure that the acoustic modem and ahead looking sonar did not interfere with each other.

The first autonomous AMMT operation was a Preliminary Performance Test with calibration of waterspeed versus propeller RPM. Hydrodynamic performance in the horizontal and vertical plans was validated with the underhull imaging pod and the added length of the mapping processor hull insert. Theoretical endurance with silver-zinc batteries was estimated 36 to 48 hours depending on speed.

During the first autonomous dive, initial insights into acoustic modem performance were obtained. The modem was relied upon heavily, not only a development technology, but as an essential tracking and status tool for the untethered vehicle. Messages were transmitted from the vehicle at operator-selected time intervals such as once per minute. Detailed status content consisted of vehicle position, velocity, attitude, keel depth, altitude above the bottom, estimates of ocean current, and subsystem status including battery and variable ballast. Data rates of 5 kilo-bits per second were achieved with the modem and image processing software later demonstrated the ability to transmit compressed images using two methods; JPEG as a baseline and a wavelets-based method. Time to transmit the compressed images was about 4 and 2 minutes respectively.

The next item in the test sequence was calibration of the inertial navigation subsystem. The vehicle was towed on the surface 45 miles north along the coast from Fort Lauderdale. Differential GPS fixes were periodically used to reset the inertial navigation position and to calibrate doppler scale factor and boresight misalignment - a one-time procedure for each vehicle installation. Upon completion of the calibration, navigation accuracy was evaluated during the return tow south. Portions of the two were conducted on the surface and later submerged for concurrent inertial navigation subsystem after 15 nautical miles was less than 10 yards and after 35 nautical miles was less than 50 yards. Refinements to the calibration process may provide further reduction in errors.

B. Diagnostic Tests

The final item remaining to be completed before further autonomous operation was Sonar Diagnostic Tow. Investment was made in the submerged tow capability in order to connect Ethernet channels from the vehicle to the Control Van to permit sonar data recording at higher rates and for longer periods than would be possible with vehicle recorders. The Diagnostic Tow umbilical also provided real-time insight into the behavior of the mapping sonar. Recording and real-time insight were invaluable for diagnostic testing in spite of some acoustic interference from the tow vessel.

A threat-representative exercise minefield was deployed to provide targets for the ahead looking sonar. About 40 bottom and moored mines were laid in water depths from 150 to 600 feet. Some mines were painted olive drab to provide a meaningful mine identification test for the imaging equipment and image compression process. Special optical targets were also placed on the ocean bottom to evaluate the dimensional and contrast resolution of the imaging systems.

A revised sonar software release was down-loaded to the vehicle's mapping processors and a limited amount of Diagnostic Tow was conducted which verified fully autonomous Computer Aided Detection of the mines. As the vehicle was towed over the exercise minefield, information passed over the umbilical allowed one to observe the system making target calls without operator intervention and noting target locations near known positions of exercise mines.

C. Autonomous Tests

Autonomous operation and testing of the mission planner came next. In a dense survey over a small area, the Mission Planner demonstrated the ability to solve and execute trajectories for lane spacing closer than the vehicle minimum turn diameter. Avoidance trajectories were demonstrated around obstacles manually entered into the pre-mission planner. At-sea performance showed close correlation with predictions based on Draper's Hybrid Simulation. Surveys over larger areas permitted fully autonomous operation of the mapping sonar. Terrain following using sonar inputs was briefly demonstrated. A "comb" survey, consisting of shoreward probes along the coast at 1 nautical mile intervals, yielded rapid reconnaissance over a large area. The UUV demonstrated its inherent stealth for clandestine reconnaissance when it surfaced for a GPS fix and re-submerged within 10 minutes. Successful test days resulted in completion of back-to-back missions of 4 hours duration. Each the single longest AMMT autonomous mission lasted 6 hours, covered 20 linear miles of survey, and mapped a 2 by 2 nautical mile area with 100% overlap.

VI. ACCOMPLISHMENTS

Significant accomplishments were achieved during the test program. In addition to meeting the four major program requirements; provide a reliable, fault tolerant integrated testbed vehicle; develop support equipment suite; provide capability to launch, recover, perform diagnostic tow and service vehicle; and select test site and mobilize for conduct of tests; many program objectives were met and test demonstrations conducted. At-sea tests included subsystem demonstrations of the various advanced technologies. However, full mission demonstrations of the program's integrated minehunting and mapping capabilities were not accomplished due to time and cost considerations.

On-line adaptive mission planning was implemented, and successful generation and execution of mission plans in varying ocean environments was demonstrated. The vehicle achieved trajectories and maintained safe operating conditions.

All preplanned mission planner activities were demonstrated at-sea, except for data upload; with the planner's contingent activities demonstrated in simulation, as the program ended before these activities could be executed at-sea.

The sonar system demonstrated the ability to perform real-time mine detection and classification by detecting all deployed targets. The ability to autonomously map bottom topography was demonstrated by generation of maps which agreed with surveyed data. The ability to track and navigate, using bottom features in the acoustic tracking navigation mode, was demonstrated over short intervals. However, the acoustic tracking navigation data was not integrated with the inertial navigation system data before the program ended.

The navigation system demonstrated it can be operated in an autonomous mode and can perform erect and align sequencing. Test data indicated performance accuracies which approached the desired goal of 0.02% of distance traveled, exceeding state-of-the-art systems in use. The results are based upon limited test data and require additional at-sea testing to establish firm quantitative values.

The acoustic communications system demonstrated reliable uplink communications from the vehicle to the host at data rates of 5 kbps up to ranges of 2 km. Uplink rates of 10 kbps were demonstrated up to ranges of 700m. Downlink communications from the host to the vehicle, typically at 2.5 kbps, were not demonstrated due to the thermal layer in the operating area and the geometries of the V-Fin positioning on the host and the directional receiver patterns of the vehicle. Image processing demonstrations showed the ability to compress optical images by either of two methods, JPEG or EPIC, and transmit the images acoustically to the host. The system was used to compress and transmit a sonar map post mission but not in real-time, before the program ended.

Optical imaging was not successfully demonstrated during AMMT Program testing. Although both the LLSS and camera were integrated into the vehicle and operated correctly producing images dockside in air, the LLSS did not produce a suitable image at desired altitudes at-sea due to environmental conditions. Autonomous imaging runs were made at conservative altitudes of 15 m, which proved to be too great for the water conditions. LLSS images were obtained at non-optimal altitudes during surface tow operations but they lack detail and recognizable objects.

Originally, the at-sea test program was designed to include an overall demonstration of the fully integrated vehicle conducting a clandestine reconnaissance mission profile, utilizing all of the advanced technologies. Specifically, the vehicle would autonomously transit 25 nautical miles, over-the-horizon, perform a minehunting and mapping survey of an area, revisit one or more of the previously detected minelike objects, image the objects with the LLSS, and compress and acoustically transmit the image and mapping products to a host. The detailed maps and images would be generated post-mission to support "quick-look" data products. Although pieces of this mission profile were demonstrated individually, they were not demonstrated collectively in one autonomous mission due to test schedule limitations.

VII. Conclusions

The AMMT Program was conceived and executed in the DARPA tradition of having aggressive goals with an aggressive schedule. At-sea testing was terminated in May 1996 before all goals were completely met, because of funding limitations and other commitments for the NSWC facility and support ship. At termination, the Program was proceeding toward completion of all goals. At the time, there were no known technical challenges which were considered insurmountable.

The AMMT Program went a long way towards proving the concepts that a complex autonomous vehicle, integrating several state-of-the-art technologies, could perform a clandestine survey of an undersea area and transmit information in near real-time such that it could be used as an effective mine countermeasure asset. Autonomous real-time mission planning was demonstrated, a first for UUVs. Navigation accuracy improvement of a factor of 5 over known system was validated. Additional testing would have received the list of demonstrated technologied achievements.

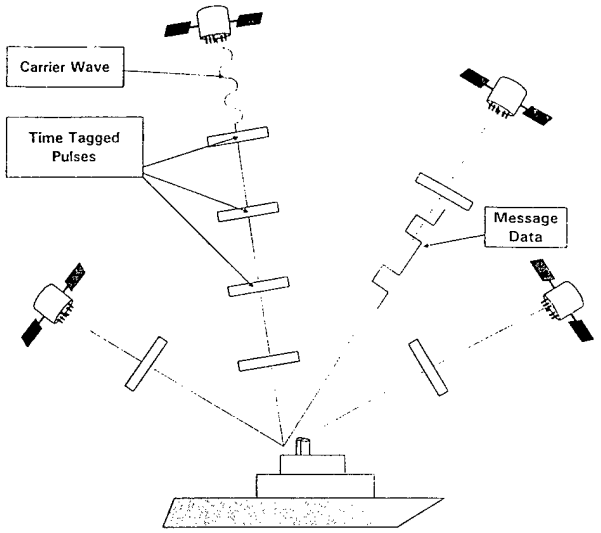
GPS and Mine Warfare

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Abstract - The Global Positioning System (GPS) is now the standard for navigation and precise positioning in the military and civilian worlds. There are many techniques for utilizing this system, all with different levels of accuracies and limitations. Techniques will be reviewed that yield accuracies between 100 m and 2 cm for dynamic platforms. Many of the latest techniques and systems are now coming out of the civilian sector. The applications of these techniques to mine warfare will be discussed, including subtle limitations. A new system under development to achieve 2 m absolute positions at sea and serve as a mobile differential GPS base station will be presented.

I. Basic GPS Information Flow

In order to understand some of the capabilities and limitations of GPS in any application, the flow of the information and the contribution of various error sources to the position error needs to be understood. [1-3] In Fig. 1 a schematic of the information flowing from the satellite to a mobile user is shown. The phrase "effective transmissions" is used because pulses and carriers are not actually present in the signal. They are regenerated in the receiver.



GPS Satellites
Effective Transmissions

Figure 1

The receiver effectively gets three types of information from each satellite: time tagged pulses that are used to generate ranges, phases of the regenerated carrier, and message data. The pulses are time tagged with time of transmission. They are converted into ranges by multiplying the time of transmission (received time minus the transmit time) by the speed of light. These are called pseudoranges. They are used to generate a position. The phases are used in a like manor to generate a velocity. In an advanced differential techniques call kinematics, these phases are used for cm level positioning.

It is the message data that generates the limitations on the GPS system for the military user. In order to use the ranges to generate a location, the position of the satellites is needed. This is obtained from a simple orbit model and coefficients contained in the message. These coefficients produce predictions of the satellite positions based on data between 2 hrs and 26 hrs old. These coefficients are called the Broadcast (BC) ephemeris. The inaccuracy in the BC ephemeris, and how the error grows with age, is the major error source for military users.

It takes a minimum of data from 4 satellites to generate a GPS three dimensional solution and the receiver time bias. The users clock error is determined at each solution time line. Modern GPS receivers utilize 6 to 12 satellites in a solution to reduce the error. Most receivers produce solutions at a 1 Hz rate. Receivers that produce 10 Hz solutions are available.

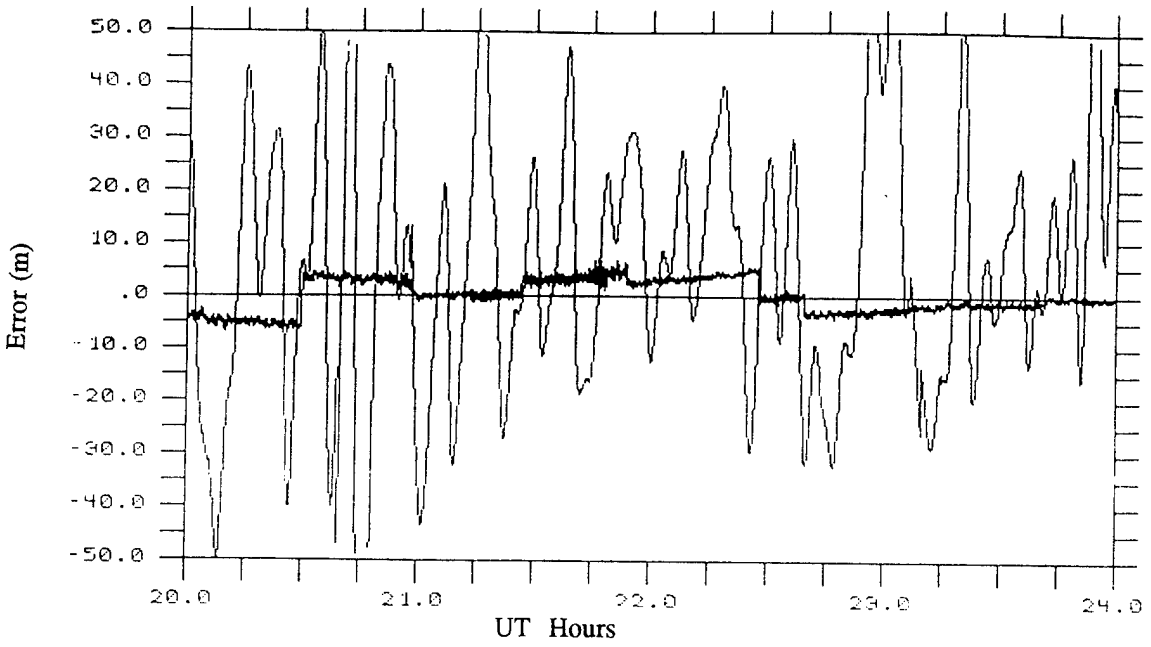
II. GPS Error Characteristics

In Fig. 2 the latitude errors from two receivers sharing an antenna are shown. The curve with the wide oscillations is taking data in the civilian Standard Positioning Service (SPS) mode. The curve with much lower errors is from a military receiver using the Precise Positioning Service (PPS). Four hours of data are plotted here on a vertical scale that spans 100 m. Both these curves may be important to the military user in precision navigation applications.

The PPS curve is quite interesting; it appears to be a series of straight lines with a very small amount of noise on them. The lines are discontinuous, with jumps of a few meters about every half hour. In fact this is a 4 channel receiver and the jumps correspond to the change of one tracking channel from one satellite to another. What is seen here is the effect of switching from one set of broadcast ephemeris errors to another. This is the error in the slow speed information channel depicted in Fig. 1.

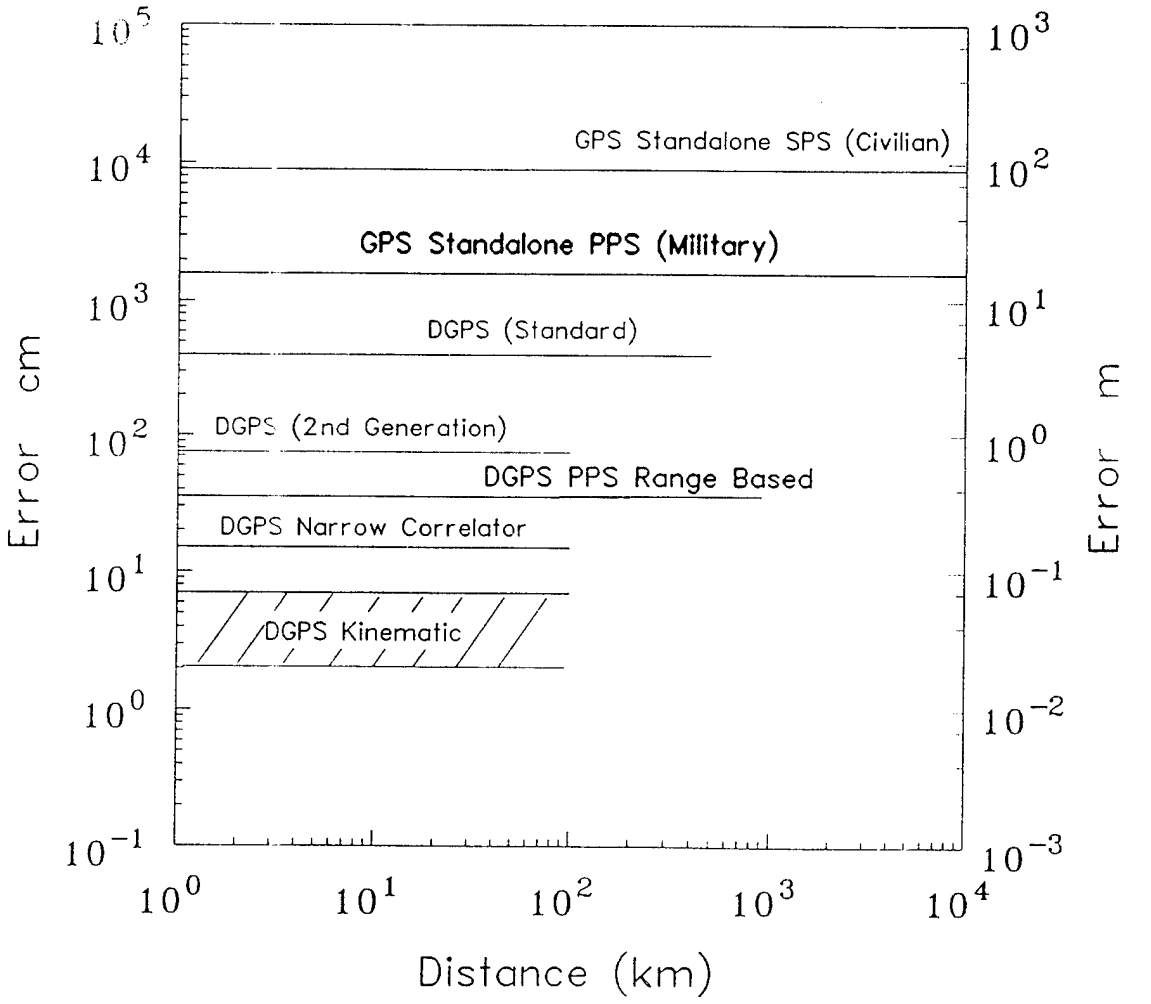
Notice that the errors are really slightly slopping lines indicating a very slow rate of change of these errors. However, if the error were determined, they could be considered constant over an hour or so. This means that if a differential system used the PPS system, it would have to transmit a very small amount of information at a rate measured in units of bits per hour. The resulting error, due to the fuzz on the PPS error lines is at the 30 cm per axis level. It should also be possible to preload corrections into a system if the mission duration is only an hour or so and still maintain this 30 cm error level.

Most differential systems operate on the SPS signal. This is because these system are developed by and for civilians for the most part. Civilian differential GPS (DGPS) systems are well developed, and there have even been a series of generations and techniques that give a variety of accuracies. From Fig. 2 the important point for SPS DGPS is the



SPS and PPS Latitude Error

Figure 2



GPS Accuracy Levels

Figure 3

rate of change of the errors. This high rate means that corrections must be sent much more often than a corresponding PPS DGPS system. In fact, the data rates are still quit modest, easily satisfied at the "low accuracy" end by 50 baud and at the high end by 9600 baud.

III. Dynamic GPS Accuracy Levels

The accuracy of various types of GPS systems is shown in Fig 3. Here the accuracy level is plotted against the separation of base and user receivers to show a rough idea of the range of DGPS systems. The left hand accuracy scale is in cm, the right in m. Both the scales on this plot are logarithmic due to the large range of values involved. These figures are for systems on mobile platforms, at dynamics up to standard aircraft accelerations.

The major point to take from this graph is that there are many different options available with a wide variety of accuracies. Most of the systems have been developed my the civilian sector, particularly the most accurate ones. Only in the area of anti-jamming are the military developments as advanced as the work being done in the civilian world. This means that turn key DGPS systems utilizing SPS signals are readily available, even for military applications.

A Standalone Accuracy

At the top of Fig. 3 are two lines that go out to the full size of the earth. These are the stand alone accuracies of a receiver in the SPS and PPS systems. [4,5] The SPS accuracy is specified in the US Federal Radionavigation Plan as 100 m 95 percent of the time in the horizontal plane. When one divides this by two to get a horizontal one sigma value, and adds the effects of the vertical errors, the total three dimensional one standard deviation for SPS is about 100 m.

The error in the vertical is unspecified in SPS, but from very general considerations one can show that it is about 1.5 times the horizontal error. The larger vertical error is due to an asymmetry in the system. One can see satellites to on all sides, but only above. There are no satellites visible below the user. This effect and ratio of errors applies to PPS and even to DGPS system.

The PPS standalone error is shown at 16 m 3-dimensional. This is the SEP (spherical error probable) value in the GPS specification. In fact the system operators are doing a little better now, often achieving about 10 m. They can and do perform better over a "limited" area. The majority of the error is due to the broadcast ephemeris which increases with the time from upload. This can be minimized by having fresher ephemeris. Currently (1996) the Air Force is optimizing the uploads to give the freshest possible ephemeris to satellites visible over europe. This decreases the error there to about 6 m. However it increases the error on the other side of the world. Because GPS satellites are at such an high altitude and can be seen over almost half the earth at once, "limited area" here means about 1/8 of the earth.

B. Differential GPS Accuracy

The other lines on Fig. 3 are for differential systems. [2,3] In this case a reference receiver is set over a known point and measures the errors in each satellites signal on a real time basis. These errors, or corrections, are transmitted by some means to the remote, often mobile, user. The remote user corrects his measurements before he computes his location and velocity. There have been several generations of receivers used in DGPS systems and are there are different processing techniques all leading to the variety of lines. The length of the lines on this graph reflects specifications and may often be greater.

The first generation of DGPS has and error of about 4 m. This generation is exemplified by the USCG system [6] for maritime use. It uses a very low data transmission rate for the corrections of 50 bits per second (50 baud). The format of the corrections used by the USCG, the RTCM-SC-104 format [7], is used by most DGPS system and accepted by all receivers that claim DGPS capabilities. There is still a large installed base of base stations and receiver of this generation.

A second generation was developed by many manufactures to "break the 1 meter level". Several succeeded, using lower noise receivers and slightly higher data rates for the corrections. These corrections were still transmitted in the USCG format but at rates of 2400 baud.

Below this level comes the PPS DGPS level of about 30 cm. [8] This is the level represented by the fuzz on the horizontal PPS line in Fig. 1. This can be a very wide area system, limited only by the requirement that the reference station and the remote user see most of the same satellites. A series of stations and a satellite relay could effectively cover the earth turning military GPS into a submeter system. Due to the low rate of change of the corrections in the PPS system, only a very low data rate in the bits/hour category would be required.

An even more accurate standard DGPS system was made possible with the introduction of a new RF hardware techniques by a Canadian company. [9] These techniques are usually denoted as "narrow correlator" technology. (The correlators are narrow in the time domain, but very broad in the frequency domain. This technique effectively uses information in the frequency sidelobes ignored in previous receiver generations.) With this technology, which is essentially used by many manufactures, gives a DGPS signal in the 15 to 20 cm range. The corrections can still be sent at 2400 baud and are in the standard RTCM format.

Even higher accuracy can be obtained if the phase information is used to find a differential position. [2,3,10,11] This technique is more complex and requires careful initialization that may take 3 to 5 minutes of data. Higher data rates for the corrections are required, typically at 9600 baud for corrections every second. Accuracies from 2 to 7 cm are typical of these systems. [12] They are usually limited to ranges of 100 km or so, particularly in the initialization phase.

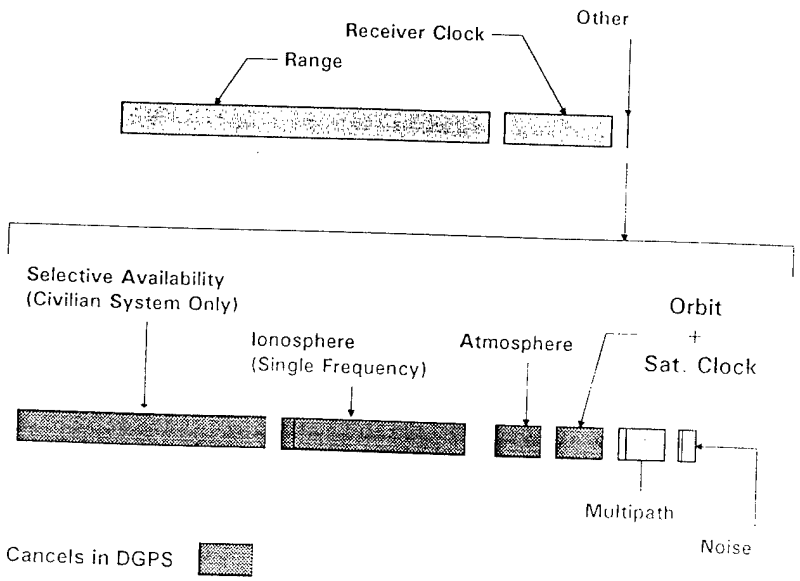
C. Base Station Location Errors

Finally a note on the "known" location of the reference receiver antenna is in order. Any error in this location will be essentially translated to errors in the remote user locations. Thus a 1 m north error in the position used for the reference will translate all differential users location 1 m north. Thus for an expeditionary situation, one could just find an approximate location for a reference station and use that for all users. A local datum would have been created, with the error being shared by all users. This is called a "floating reference system".

IV. GPS and Underwater Vehicles

GPS signals do not penetrate seawater. Only a few mm will effectively block them. [13] Accordingly, for underwater vehicles an antenna must be placed above the surface in order to get a position. An antenna does not need to permanently be on the surface, a pop up of the antenna will do.

The time the antenna needs to be up varies greatly with several factors. First different vendors vary a great deal in the time to fix (solution). In addition the past tracking history can be important. If the receiver thinks it knows the approximate range of the satellite and the Doppler offset frequency, the acquisition can be very rapid. This can be 2 to 5 seconds in receivers optimized for reacquisition. Receivers are available that can get ranges from 4 or more satellites in about 10 sec if they have been tracking these satellites in the past hour of so.



Components of GPS Range Measurement

Figure 4

In order to do a real time navigation solution, the receiver must have not only the range measurements, but also the coefficients in the message that determine the location of the satellites. It takes 30 seconds for this data to be received. Therefore it often takes 40 - 60 s to get a first fix on the best receivers if it has no ephemeris. However these ephemeris can be preloaded or a periodic extended tracking period can be used to acquire them. They are nominally good for 6 hrs.

If real time navigation is not required, then only range data is needed. In this case the solutions can be generated post mission using ephemeris collected by another receiver.

V. GPS Error Sources

The errors in position solutions using GPS are rooted in errors in the measurements of ranges and phases of the satellite signals, in the broadcast ephemeris, and in any differential corrections. The errors enter into the solutions with a multiplicative factor. [1-3] Assuming that the range measurement errors are about the same magnitude from all satellites:

$$\text{Solution Error} = \text{DOP} \times \text{Range Error}$$

Here the DOP, or Dilution of Precision, is the multiplicative factor. It is generally between 1.5 and 12 with values less than 6 being considered acceptable. DOP is basically a measure of how spread out the satellites are in the sky. If all the satellites are in one segment, the DOP will be large. (There are other bad geometries. For example if three satellites are along a great circle, only two are useful.)

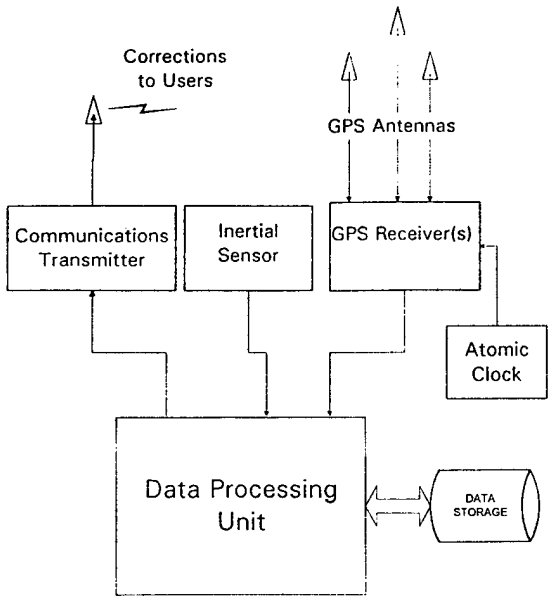
The errors in a range measurement are shown in Fig 4. The true range and the receiver clock error are used in the solution. The receiver clock error is a part of the solution at each time line allowing very inexpensive oscillators to be used. All the range errors that contribute to solution error are contained in the small sliver that has been expanded. Most of these errors originate in the satellite or in the atmosphere. They are essentially identical for close receivers and are removed in DGPS. Only the site specific errors, the receiver thermal noise and the multipath are not canceled. Multipath is the error generated when the signal enters the antenna after bouncing off some object. In general the receiver cannot distinguish this signal from the direct path and a composite of the two is measured.

The Selective Availability error (SA) is intentionally introduced to degrade the position accuracy of SPS users. It is about 30 m and causes the large oscillations in Fig. 1. It is not periodic however, following a complex path designed to be hard to filter out. The ionospheric error is normally not present in military receivers because they often use two frequencies. The second frequency is there just to remove this error. However the Precision Lightweight GPS Receiver (PLGR) is a single frequency receiver. The second frequency is unavailable to inexpensive civilian receivers. This has lead to most DGPS systems being signal frequency systems. The atmospheric error is about 2 m vertically and more for paths at lower elevation angles.

The orbit and satellite clock error is the most important one for military users. It is caused by the ageing of the information in the broadcast ephemeris. These model positions of the satellite position are predictions of where the satellite will be in the future. Data used for these prediction can be from 2 to 26 hours old. The current positions are always known at the control center in Colorado Springs, but the once/day upload cycle only delivers aged data to the user. The error grows slowly however, and only a very low update rate would be required to provide the military user with current information. Of course this is effectively what is done in all DGPS systems.

VI. Shipborne Reference System

The Naval Postgraduate School is currently developing a system to serve as a differential base station on a ship. There are many problems that a shipborne reference system (SRS) will encounter that are absent or can be avoided with land reference sites. The most obvious complication is that the antenna is moving. However there are other issues, such as the inevitable multipath on a ship. A multisensor system has been proposed to solve all these problems. A block diagram of the SRS is shown in Fig. 5.



GPS Ship Reference System

Figure 5

The system will consist of one to three GPS receivers. The multiple receivers will be used to average down the multipath. Therefore the antennas will have to be fairly widely separated, at least by 3 to 6 m (one to two P-code chips) to give independent multipath measurements. Of course the measurements from these antennas will have to be brought together, and orientation information is needed for that.

The orientation might be obtainable at the required accuracy from the three antennas themselves. However multipath errors might alias into this estimation. Therefore an inertial sensor has been added to the system. This sensor will also allow the system to coast over outages such as passage under a bridge. The inertial sensor will also add considerably to the tracking of the antenna motions over ship roll periods. This inertial can be of modest accuracy, with error characteristics on the order of 1 deg/hr.

The motion of the ship will be tracked using the phase data, which is about 1000 times as accurate as the ranging data. The inertial will be useful here in detecting cycle slips and in averaging over residual phase multipath. Once a solution is initialized, the system should be able to keep track of the motion of the antennas at a level below a wavelength, that is in the 10 to 20 cm range.

The key item being averaged out is the orbit and clock error in the broadcast ephemeris. Having to estimate individual orbit clock errors means that the system cannot depend entirely on the GPS satellite clocks to estimate user clock errors. To solve this problem an atomic oscillator will drive all the receivers. It is not clear that the ship clock bias can be obtained at the nsec level, but drifts should be well controlled and only biases should remain.

The key to the system is a data processing unit that will process a very large quantity of data in a batch mode to initialize the system. With modern computers and large disks it will be possible to keep and analyze one or two days of 1 sec data from multiple receivers. The use of batch mode will made the detection of cycle slips and bridging data gaps easier by a factor of 4 than a Kalman filter. Once initialized the system should maintain the solution via kinematics (phase based solutions) at a high precision, but with some much larger bias. The initialization process does not need to stop with the availability of computer power today. It can be run every few hours and the new initialization will serve as an integrity check on the ongoing solution.

A simple error model has been developed for this system. There are inputs for the amount of multipath, the GPS receiver noise level, and the

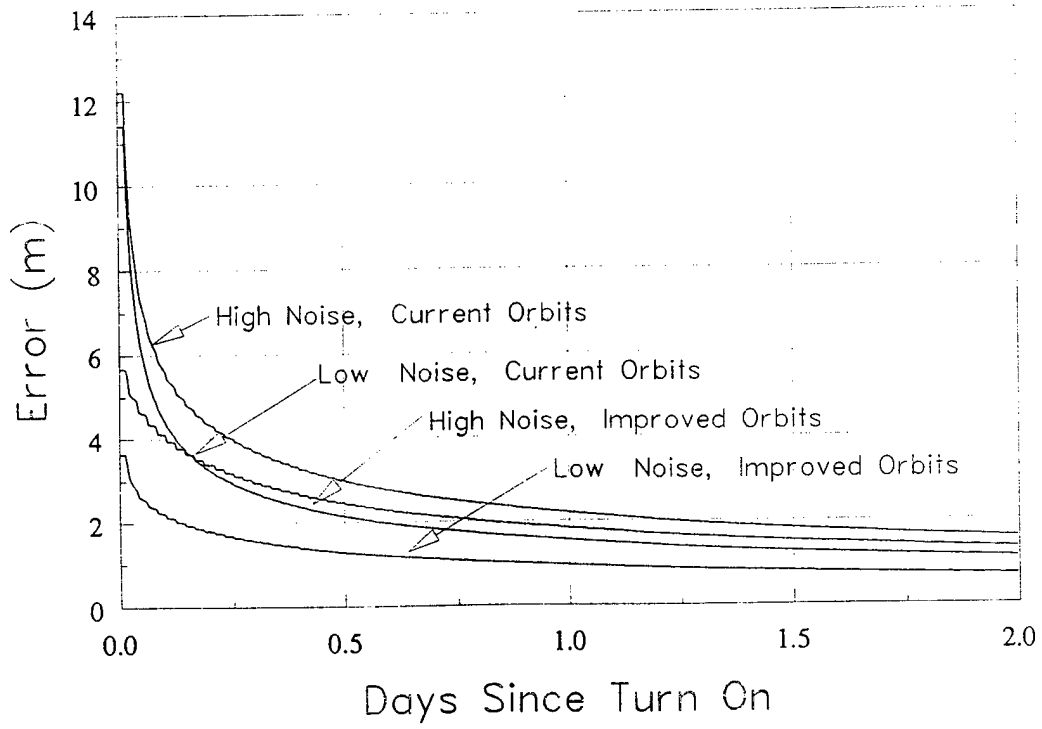


Figure 6

broadcast ephemeris error level. It is assumed that the error in a BC ephemeris will be a straight line over the entire pass (3 to 6 hours). It will therefore take many hours to average down this error as independent samples only occur as new satellites come into view. The GPS Joint Program office has a program underway to improve the BC ephemeris. Both the current level and the proposed level have been considered.

A plot of the initialization error against the time since startup is given in Fig 6 where 4 cases are shown. A conservative case with current orbits, high receiver noise level and high multipath shows the solution converging to the 2 m level in about 30 hrs (1.25 days). The best case, of improved orbits, low receiver noise, and low multipath has obtains a 2 m solution in 6 hours and a 1 m solution in a day.

This system is currently under development at the Naval Postgraduate School. It is planned to demonstrate a system at sea in FY 98. The work on the Shipborne Reference System is sponsored by the Office of Naval Research.

VII. Conclusions

The accuracy levels available to mine warfare operators covers a large range from 10 m to 30 cm utilizing various techniques. Very good results are obtained with a PPS differential system which need only transfer a few bytes per hour from the reference station to the users. The sources of the errors and techniques to deal with them have been discussed. Finally a system to obtain 1 to 2 m absolute positions on a ship has been discussed.

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The *Phoenix* Autonomous Underwater Vehicle

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Abstract. The *Phoenix* autonomous underwater vehicle (AUV) is a robot for student research in shallow-water sensing and control (Figure 1). *Phoenix* is neutrally buoyant at 387 pounds (176 kg) with a hull length of 7.2 feet (2.2 m). Multiple propellers, thrusters, plane surfaces and sonars make this robot highly controllable. The underwater environment provides numerous difficulties for robot builders: submerged hydrodynamics characteristics are complex and coupled in six spatial degrees of freedom, sonar is problematic, visual ranges are short and power endurance is limited. Numerous *Phoenix* contributions include artificial intelligence (AI) implementations for multisensor underwater navigation and a working three-layer software architecture for control. Specifically we have implemented the execution, tactical and strategic levels of the Rational Behavior Model (RBM) robot architecture. These three layers correspond to hard-real-time reactive control, soft-real-time sensor-based interaction, and long-term planning respectively. Operational software functionality is patterned after jobs performed by crew members on naval ships. Results from simple missions are now available.

In general, a critical bottleneck exists in AUV design and development. It is tremendously difficult to observe, communicate with and test underwater robots because they operate in a remote and hazardous environment where physical dynamics and sensing modalities are counterintuitive. Simulation-based design using an underwater virtual world has been a crucial advantage permitting rapid development of disparate software and hardware modules. A second architecture for an underwater virtual world is also presented which can comprehensively model all necessary functional characteristics of the real world in real time. This virtual world is designed from the perspective of the robot, enabling realistic AUV evaluation and testing in the laboratory. 3D real-time graphics are our window into the virtual world, enabling multiple observers to visualize complex interactions.

Networking considerations are crucial within and outside the robot. A networked architecture enables multiple robot processes and multiple world components to operate collectively in real time. Networking also permits world-wide observation and collaboration with other scientists interested in either robot or virtual world. Repeated validation of simulation extensions through real-world testing remains essential. Details are provided on process coordination, reactive behaviors, navigation, real-time sonar classification, path replanning around detected obstacles, networking, sonar and hydrodynamics modeling, and distributable computer graphics rendering. Finally in-water experimental results are presented and evaluated.

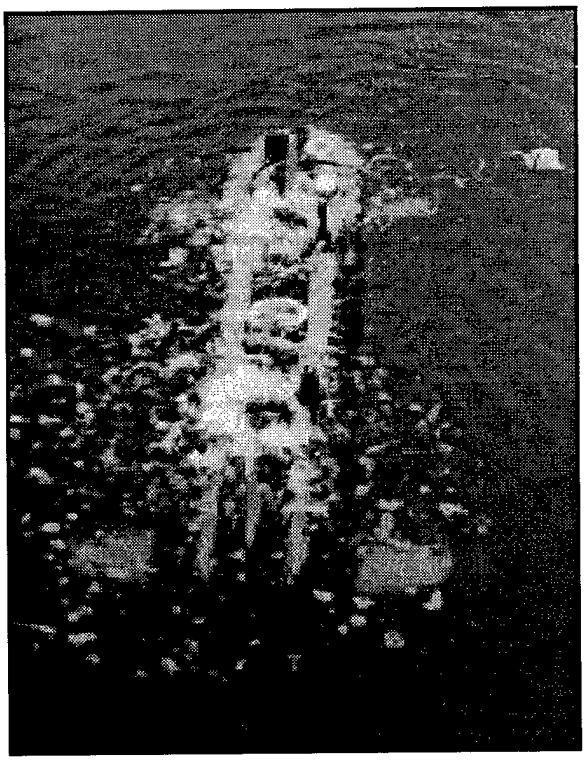


Figure 1. *Phoenix* AUV testing in Moss Landing Harbor, California.

1 INTRODUCTION

This work describes software architectures for an autonomous underwater robot and for a corresponding underwater virtual world, emphasizing the importance of 3D real-time visualization in all aspects of the design process. Recent work using the *Phoenix* AUV is notable for the successful implementation and integration of numerous software modules within

multiple software layers. The three-layer software architecture used is the Rational Behavior Model (RBM), consisting of reactive real-time control (execution level), near-real-time sensor analysis and operation (tactical level), and long-term mission planning and mission control (strategic level) (Byrnes 96) (Marco 96b). In effect a higher robot software layer also exists: an off-line mission assistant that uses rule-based constraints and means-ends analysis to help human supervisors specify mission details, followed by automatic generation of strategic level source code. Results for simultaneous operation of the three onboard robot software layers (running an autogenerated mission) have been verified by virtual world rehearsal and in-water testing (Davis 96a, 96b).

Theoretical development stresses a scalable distributed network approach, interoperability between models, physics-based reproduction of real-world response, and compatibility with open systems standards. Multiple component models are networked to provide interactive real-time response for robot and human users. Logical network connectivity of physical interactions is provided using standard sockets and the IEEE standard Distributed Interactive Simulation (DIS) protocol (IEEE 95). Implementation of the underwater virtual world and autonomous robot are tested using the actual *Phoenix* AUV (Figure 2).

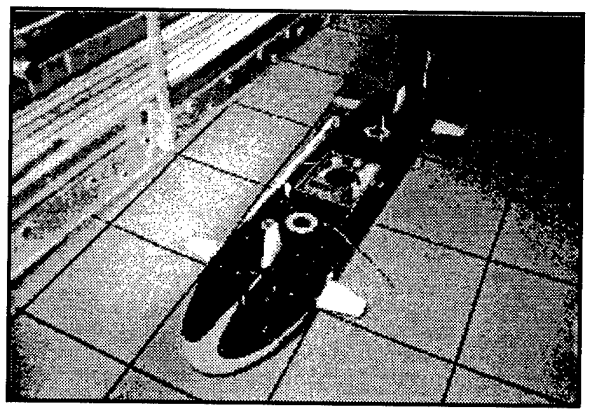


Figure 2. *Phoenix* AUV shown in test tank (Torsiello 94).

In order support repeatability of our results, documentation and source code are available electronically (Brutzman 96b, 96c). Current work includes model validation as well as adapting hydrodynamics and controls coefficients for other submersibles. Ongoing work also includes making 3D graphics and networking compatible with the Virtual Reality Modeling Language (VRML 2.0), to permit Internet-portable rendering and interaction via any computer connected to the World Wide Web.

Chapter Organization. Section 2 presents motivations for artificial intelligence (AI) approaches in underwater robotics. Section 3 describes robot hardware for *Phoenix*. Sections 4 through 7 examine the Rational Behavior Model (RBM) software architecture, detailing the execution, tactical and strategic levels. Section 8 describes robot networking. Sections 9 and 10 discuss virtual world design criteria and visualizing control algorithms. Section 11 presents AUV-virtual world communications which permit real-time physics-based response in the laboratory. Sections 12 and 13 discuss interactive 3D computer graphics and sonar visualization. Section 14 evaluates experimental results. Section 15 points out areas for future work. The chapter closes with conclusions, references, and pointers to a repository for software and documentation.

2 MOTIVATION

Untethered underwater robots are normally called Autonomous Underwater Vehicles (AUVs), not because they are intended to carry people but rather because they are designed to intelligently and independently convey sensors and payloads. AUVs must accomplish complex tasks and diverse missions, all while maintaining stable physical control with six spatial degrees of freedom (i.e. posture, meaning 3D position plus 3D orientation).

The underwater environment is highly challenging. Hydrodynamics forces are surprisingly cross-coupled between various axes because of asymmetric vehicle geometry and the nonlinear drag "added mass" of water fluid carried along with moving vehicles. Active sonar returns provide precise range but poor bearing accuracy, and can be subject to frequent dropouts. Sonar range maxima are highly frequency-dependent. At moderate ranges (beyond several hundred meters) sonar paths can bend significantly due to continuous refraction from sound speed variation, which is caused by changes in water temperature, salinity and pressure (i.e. depth). Vision is only possible for short ranges (tens of meters at best) and is often obscured if water is turbid. Underwater vision also requires powerful lighting, which is an unacceptable power drain due to already-severe power and propulsion endurance constraints. Laser sensors are usable to approximately 100 m range and provide good range and bearing data, but remain expensive, hard to tune and subject to turbidity interference. Typically little or no communication with distant human supervisors is possible. When compared to indoor, ground, airborne or space environments, the underwater domain typically imposes the most restrictive physical control and sensor limitations upon a robot. Underwater robot

considerations remain pertinent as worst-case examples relative to other environments (Figure 3).

- **Complex Hydrodynamics**
  - coupled in six spatial degrees of freedom
  - accompanying "added mass" of water
  - instability can be severe or fatal
- **Sonar**
  - accurate ranges but bearings poor
  - numerous nonlinear factors affect reverberation and attenuation
  - sonar path bending at long ranges due to sound speed profile (SSP) effects
- **Vision and Laser**
  - range limited by turbidity
  - lighting requires excessive power
- **Endurance typically a few hours**
  - limited power available
  - constrains all other equipment
- **Navigation**
  - ocean currents vary with time, location
  - acoustic navigation requires calibrated prepositioned transponder field
  - GPS and inertial methods possible
- **Communications**
  - tether is an unacceptable encumbrance
  - acoustic limited in bandwidth, range
  - optical extremely limited range

Figure 3. Environmental constraints for underwater robots are severe.

A large gap exists between the projections of theory and the actual practice of underwater robot design. Despite numerous remotely operated vehicles (ROVs) and a rich field of autonomous robot research results, few complete AUVs exist and their capabilities are limited. Cost, inaccessibility and scope of AUV design restrict the number and reach of players involved. Interactions and interdependencies between hardware and software problems are poorly understood. Equipment reliability and underwater electrical connections are constantly challenging. Testing is difficult, tedious, infrequent and potentially hazardous. Meaningful evaluation of results is hampered by overall problem complexity, sensor inadequacies and human inability to directly observe the robot *in situ*. Potential loss of an autonomous underwater robot is considered intolerable due to tremendous investments in time and resources, the likelihood that any failure will become catastrophic, and difficulty of underwater recovery.

Underwater robot progress is slow and painstaking for other reasons as well. By necessity most research is performed piecemeal and incrementally. For example, a narrow problem might be identified as suitable for solution by a particular AI paradigm and then examined in great detail. Conjectures and theories are used to create an implementation which is tested by building a model or simulation specifically suited to the problem in question. Test success or failure is used to interpret validity of conclusions. Unfortunately, integration of the design process or even final results into a working robot is often difficult or impossible. Lack of integrated testing prevents complete verification of conclusions.

AUV design must provide autonomy, stability and reliability with little tolerance for error. Control systems require particular attention since closed-form solutions for many hydrodynamics control problems are unknown. AI methodologies are thus essential for numerous critical robot software components. Historically, the interaction complexity and emergent behavior of multiple interacting AI processes has been poorly understood, incompletely tested and difficult to formally specify (Shank 91). We are happy to report that these problems can be overcome. Our three-layer robot software architecture, in combination with a physically and temporally realistic virtual world, has enabled effective research, design and implementation of an autonomous underwater robot.

The charter of the Naval Postgraduate School (NPS) Center for AUV Research group is to support graduate student thesis research. Certainly there is no shortage of problems that underwater robotics researchers might work on. We believe that having a clear and compelling objective is fundamentally important. Mission drives design. A well-defined goal provides priorities that can be understood by a large research group, clear criteria for making difficult design tradeoffs, and a finish line: success metrics are defined. We have chosen shallow-water minefield mapping as our driving application. At the 1995 Symposium on Autonomous Vehicles for Mine Countermeasures (MCM) (Bottoms 95), consensus was reached that all technical components exist which are needed to build effective MCM AUVs. Our motivating goal is to demonstrate such a vehicle. We intend to demonstrate that there are no fundamental technical impediments to mapping shallow-water minefields using affordable underwater robots. We are integrating component technologies necessary for underwater autonomy in a working system, and are making good progress toward reaching that goal.

Related efforts. Over a dozen other research groups are active in underwater robotics. The Massachusetts Institute of Technology (MIT) Sea Grant has deployed several *Odyssey*-class AUVs notable for open-ocean and under-ice oceanographic

exploration leading to the possibility of autonomous oceanographic sampling networks (AOSNs) (Curtin 93). The Florida Atlantic University (FAU) ocean engineering department has built a series of vehicles which include fuzzy logic controllers and special sensing techniques (Smith 94). The Woods Hole Oceanographic Institute (WHOI) Deep Submergence Lab (DSL) has specialized in long-term bottom monitoring, acoustic communications and remotely teleoperated task-level supervision of manipulators (Sayers 96). An excellent introductory text on underwater robot design and control is (Yuh 95). Annual AUV technical symposia are sponsored in alternate years by the IEEE Oceanic Engineering Society (OES) (*http://auvibm1.tamu.edu/oes*) and the Autonomous Undersea Systems Institute (AUSI) (*http://www.cdps.maine.edu/AUSI*).

Important problem domain for AI. Despite many handicaps, the numerous challenges of operating in the underwater environment force designers to build robots that are truly robust, autonomous, mobile and stable. This fits well with a motivating philosophy of Hans Moravec:

> .. solving the day to day problems of developing a mobile organism steers one in the direction of general intelligence... Mobile robotics may or may not be the fastest way to arrive at general human competence in machines, but I believe it is one of the surest roads. (Moravec 83)

3 HARDWARE

Detailed knowledge regarding robot capabilities and requirements are necessary prerequisites for designing and implementing robot software. Overview descriptions of the *Phoenix* AUV and related research appear in (Brutzman, Compton 91). Both an external view and internal vehicle component arrangements are shown in Figures 4 and 5.

Designed for research, the *Phoenix* AUV has four paired plane surfaces (eight fins total) and bidirectional twin propellers. The hull is made of pressed and welded aluminum. The vehicle is ballasted to be neutrally buoyant at 387 lb (176 kg) with a hull length of 7.2 ft (2.2 m). Design depth is very shallow at 20 ft (6.1 m). Two pairs of sealed lead-acid gel batteries provides vehicle endurance of 90-120 minutes. Since battery electrical discharge produces hydrogen gas, hydrogen absorber pellets reduce the potential hazard of explosion. Twin propellers provide 5 pounds of force (lbf) (22.5 N) with resulting speeds up to 2 knots (~1 m/sec). A free-flooding (vented to water) fiberglass sonar dome supports two forward-looking sonar transducers, a downward-looking sonar altimeter, a water speed flow meter and a depth pressure cell. Five rotational gyros mounted internally are used to measure angles and rates for roll, pitch and yaw respectively. Small cross-body thruster tunnels were locally designed and built for the *Phoenix* AUV. An in-line bidirectional propeller inside each thruster can provide up to 2 lbf (8.9 N). Detailed schematics and specifications of all *Phoenix* AUV hardware components are presented in (Torsiello 94).

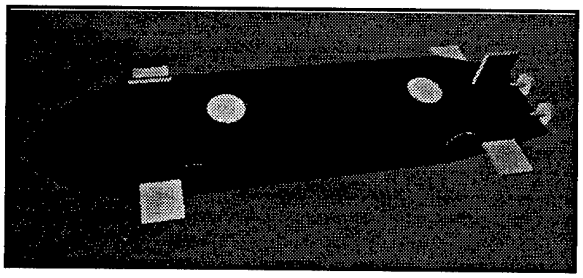


Figure 4. Exterior view of NPS *Phoenix* AUV.

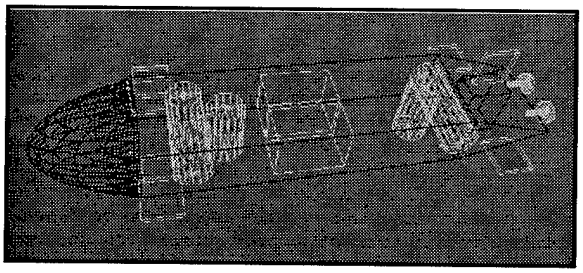


Figure 5. Internal view of NPS *Phoenix* AUV.

The primary computer for low-level hardware control is a GesPac 68030 running the OS-9 operating system. A significant recent hardware improvement was addition of a Sun Sparc 5 "Voyager" laptop workstation, with the display monitor removed to save space. Also connected is a paddlewheel speed sensor, depth sensor, DiveTracker acoustic navigation system (Flagg 94), Geographic Positioning System (GPS), Differential GPS (DGPS) and inertial navigation system (INS) equipment (Bachmann 96), as well as Ethernet local-area network (LAN) connections between onboard computers and (optionally) to external networks. Twin sonars have 1 cm resolution out to 30 m maximum range, with the ST725 (725 KHz) having a 1° wide by 24° vertical beam, and the ST1000 (1 MHz) a 1° conical beam. Each sonar is steered mechanically in 0.9° increments.

4 SOFTWARE OVERVIEW

The *Phoenix* AUV is primarily designed for research on autonomous dynamic control, sensing and AI. Software control of the vehicle is provided at a low level corresponding to maneuvering control of plane surfaces and propellers, as well as at a high level

corresponding to strategic planning and tactical coordination. Sensors are also controlled via execution level microprocessor-hardware interfaces, although some sensor functions may be optionally commanded by the intermediate tactical level, such as steering individual sonar transducer heading motors during classification.

Due to the large variety of critical tasks an autonomous underwater robot must perform, a robust multilevel software architecture is essential. Underwater robot software architectures are a particular challenge because they include a many of the hardest problems in robotics, control and AI over short, medium and long time scales.

Rational Behavior Model (RBM). The software architecture used by the *Phoenix* AUV is the Rational Behavior Model (RBM) (Byrnes 93, 96). The Rational Behavior Model (RBM) is a trilevel multiparadigm software architecture for the control of autonomous vehicles. Execution, tactical and strategic levels correspond roughly to direct interaction with vehicle hardware and environment, intermediate computational processing of symbolic goals, and high-level planning, respectively. The three levels of RBM correspond to levels of software abstraction which best match the functionality of associated tasks. Temporal requirements range from hard-real-time requirements at the execution level, where precise control of vehicle sensors and propulsion is necessary to prevent mission failure or vehicle damage, to soft-real-time long-term planning at the strategic level.

RBM provides an overall structure for the large variety of *Phoenix* AUV software components. A particular advantage of RBM is that the three levels of RBM can be informally compared to the watchstanding organization of a submarine crew (i.e. a manned AUV). Watchstanders operating vehicle sensors, the propulsion plant and diving station controls correspond to the execution level. Precise real-time control is needed at this level. The Officer Of the Deck (OOD) is represented in the tactical level, carrying out Commanding Officer (CO) orders by sending individual commands capable of being carried out by watchstanders at the execution level. Due to the diversity of tactical tasks and the complexity of some orders from the CO, the OOD has assistants at the tactical level to assist in their decomposition. These departments (navigation, sonar, path replanner etc.) permit the OOD to concentrate on sequencing and coordinating overall vehicle operation rather than exhaustively directing every detail. Finally the CO is responsible for mission generation and successful completion. CO tasks include mission-related planning and decision making, all performed at the strategic level. This architectural relationship is illustrated in Figure 6 (Holden 95).

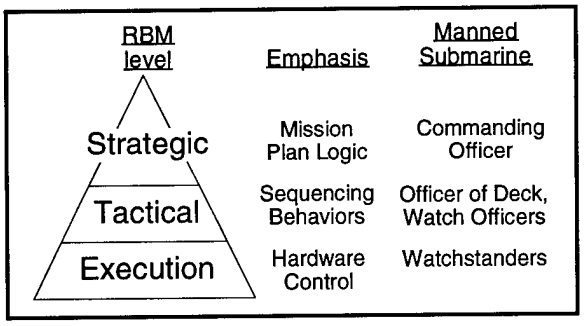


Figure 6. Rational Behavior Model (RBM) software architecture (Holden 95).

Human analogies are particularly useful for naval officers working on this project who already know how to drive ships, submarines and aircraft, since they provide a well-understood partitioning of duties and a clearly defined task lexicon. The naval analogies used here merely express common and essential robotics requirements using terminology familiar to the many officer students who have worked on *Phoenix*. This approach permits them to intuitively apply at-sea experience and domain knowledge. The RBM paradigm continues to serve well as a formal robot architecture which scalably composes numerous critical processes having dissimilar temporal and functional specifications.

RBM three levels summarized. Execution level software integration includes physical device control, sense-decide-act, reactive behaviors, connectivity, a mission script language, and stand-alone robustness in case of loss of higher levels. Tactical level software includes Officer of the Deck (OOD) coordination of parallel tactical processes, telemetry vector state variable updates as a form of shared memory, sonar control, sonar analysis and classification, path planning, DiveTracker acoustic navigation, DiveTracker acoustic communications, DGPS/GPS/INS navigation, and fail-safe mission abort if strategic level commands are lost. Strategic level software integration includes cross-language message passing, linking dissimilar binary executables, and several functionally equivalent strategic level variations: missions prescribed by Prolog rules, static mission scripts or an off-line mission generation expert system. There are numerous three-level robot architectures and many are similar to RBM.

Operating Systems and Compilers. Interestingly enough, operating system and compiler considerations have been most notable for their incompatibilities rather than their power. Aside from multitasking and

interprocess communications, we have not yet found it necessary (or desirable) to take advantage of real-time operating system constructs. The execution level resides on a GesPac 68030 under OS-9 written in Kernighan and Richie (K&R) C, a precursor to ANSI C. The tactical and strategic levels currently reside on the Voyager Sparc 5 laptop under Solaris Unix, written in ANSI C and Prolog respectively. Additionally, tactical and execution software can identically compile under SGI Irix 5.3 Unix in ANSI C. Compilation of single version source files across a variety operating system architectures and language variants is achieved through use of `#ifdef` and *Makefile* constructs (Brutzman 96c). This prevents "versionitis" or multiple file versions which inevitably lead to programmer confusion, incompatible source code interoperability and wasted effort. We are continuing this interoperability trend by porting to the well-supported public domain compiler *g++* (GNU ANSI C/C++).

Hierarchical versus reactive. Only a few years ago, robot architecture designers seemed preoccupied with bipolar arguments between hierarchical and reactive approaches. Hierarchical stereotypes included phrases like deliberative, symbolic, structured, "top down," goal-driven, explicit focus of attention, backward inferencing, world models, planning, search techniques, strictly defined goals, rigid, unresponsive in unpredicted situations, computation-intensive, and highly sophisticated performance. Reactive stereotypes included phrases like subsumptive, "bottom up," sensor-driven, layered, forward inferencing, robust subsuming behaviors, avoid both dynamic planning and world models, behave somewhat randomly, succeed without massive computations using well-considered behaviors, difficulty scaling up, elusive stability and nondeterministic performance. RBM is a hybrid architecture that is hierarchical at the top layer, reactive at the bottom layer and a mixture in between. Real-time responsiveness varies correspondingly at each level. From our experience with *Phoenix* it appears clear that a three-layer hybrid architecture is essential for a robot that must meet a broad range of timing requirements. Similar three-layer hybrid architectures now appear to be the norm for many mobile robots.

World models. Numerous *Phoenix* AUV theses and source code implementations have been handicapped by inadequate end-to-end hardware and software functionality within the vehicle. Such constraints are common for AUVs. Availability of networked hydrodynamics and sonar models for integrated simulation during robot development have been invaluable for development of robot control algorithms. This approach has permitted realistic development of software in all three software levels, independently and in concert, first in the virtual world and then in the real world.

Declaring that combined models create a virtual world rather than a simulation is not an overstatement. From the robots perspective, the virtual world can effectively duplicate the real world if robot hardware/software response is identical in each domain. In effect, this is a type of Turing test from the robot's perspective. Such a concept is controversial, perhaps especially among reactive behavior-based approaches which assume world models are unavoidably overcomplicated and use "the world is its own best model" (Brooks 86). In our case the challenges of the underwater environment eliminate relying on world availability throughout robot development. Development of a virtual world architecture that can realistically support the robot architecture has produced a new paradigm for robot software development (Brutzman 92a, 93, 94).

5 EXECUTION LEVEL

Disaster and divergence. In 1994 the execution level was the only software which effectively existed inside the *Phoenix* AUV. A second networked version of execution level was adapted to run in conjunction with developmental tactical routines and the underwater virtual world. A disastrous hydrogen explosion occurred in 1994 which required over a year to repair. During this reconstruction period many changes and enhancements were made to the AUV software. Unfortunately the two versions of execution level software grew far apart as they progressed, with the in-water version emphasizing new hardware interfaces (Healey, Marco 95) and the virtual world version emphasizing increased functionality (Brutzman 94).

Two versions into one. The top priority for 1995 efforts was to merge the two different versions of the execution level. The in-water code was painstakingly reintegrated with the virtual world version, one function at a time. This approach permitted frequent testing in the virtual world as well as continuous execution level accessibility to other tactical level work which proceeded in parallel. Laboratory bench tests were also conducted to ensure that software functions controlled the proper hardware and direction of rotation of moving components was correct. A single version of the combined execution level source code had to run on different computer architectures, using different compilers, and with different physical and logical interfaces. The new source code also had to run identically in the real world and the virtual world, all without error. This effort was successful (Burns 96) (Brutzman 96a).

Telemetry state vector. The execution level runs in a tight sense-decide-act loop and provides real-time control of vehicle sensors and effectors. Sensor data and effector orders are recorded in a telemetry state vector. This state vector is updated at the closed loop repetition rate, typically 6-10 Hz. The state vector is used for mission data recording, sharing critical parameters among all tactical processes, and providing a data-passing communications mechanism which permits identical operation in the real world and the virtual world (described later). State vector parameters, message-passing semantics and relation to flow of control are described in detail in (Brutzman 94).

Vehicle control. As current AUV research indicates, a great variety of control modes are possible when controlling vehicle posture and movement. A primary goal for the execution level is to provide robust open-loop and closed-loop control using propellers, cross-body thrusters and fin surfaces. Direct open-loop control of all these effectors is available, singly or in combination. Closed-loop control is available for course, depth and position, either in waypoint-follow mode or hover mode. Waypoint-follow mode relies on propellers and plane surfaces, which works well while transiting but poorly when stationary. Hover mode relies on propellers for short-range longitudinal motion, and thrusters for lateral/vertical/rotational motion. Hover mode allows precise station keeping in position, heading and depth, at least while dead-reckon position and ocean current set/drift estimates are accurate.

Mission script language. In keeping with our goal to make vehicle control understandable, we have implemented execution level functionality using a series of script commands. Each command consists of a keyword followed by a variable number of parameters. The mission script language controls operating modes and state flags in the execution level. A subset of the mission script language appears in Figure 7.

Commands can originate from tactical level processes, a prepared mission script file or a human operator. Each command is designed to be unambiguous and readable either by the robot or by people. Prescripted missions and tactical communications are intelligible because they sound similar to OOD orders and ship control party communications aboard ship. We believe this approach has general applicability for most AUVs. Another feature is text-to-speech conversion in the virtual world, simplifying human monitoring of mission progress. Overall execution level functionality also includes plotting telemetry results, replaying recorded mission telemetry data, and acting as network interface to sensor and hydrodynamics models when operating in the virtual world.

```
HELP                Provide keywords list
WAIT          #     Wait/run for # seconds
WAITUNTIL     #     Wait/run until clock time
QUIT                do not execute any more
RPM     # [##]      Prop ordered rpm values
COURSE        #     Set new ordered course
TURN          #     Change ordered course #
RUDDER        #     Force rudder to # degrees
DEPTH         #     Set new ordered depth
PLANES        #     Force planes to #
THRUSTERS-ON        Enable vertical and
                    lateral thruster control
NOTHRUSTER          Disable thruster control
ROTATE        #     open loop rotation
control
NOROTATE            disable open loop rotate
LATERAL       #     open loop lateral control

GPS-FIX             Proceed to shallow depth,
                         take GPS fix
GPS-FIX-COMPLETE    Surface GPS fix complete
GYRO-ERROR    #     Degrees of gyro error
                    [GYRO + ERROR = TRUE]
LOCATION-LAB        Vehicle is operating in
                    lab using virtual world.
LOCATION-WATER      Vehicle is operating in
                    water w/o virtual world.
POSITION  # ## [###]   reset dead reckon
                    i.e. navigation fix.
ORIENTATION  # ## ###  (phi, theta, psi)
POSTURE #a #b #c #d #e #f
              (x, y, z, phi, theta, psi)
OCEANCURRENT  #x #y [#z]
TRACE         verbose print statements
STANDOFF      #     Change standoff distance
                    for WAYPOINT-FOLLOW,
HOVER
WAYPOINT      #X #Y [#Z]
HOVER         [#X #Y] [#Z] [#orientation]
              [#standoff-distance]
```

Figure 7. Mission script language (from file *mission.script.HELP*) (Brutzman 94).

6 TACTICAL LEVEL

Officer of the Deck (OOD) Coordination. Of the three levels of the RBM architecture, the tactical level

was the last developed onboard *Phoenix*. Creation of an OOD module is crucial. The OOD controls the flow of information between other levels and within the tactical level, yet cannot become overburdened by unnecessary details. By forking parallel processes, the OOD creates several departments which are available to assist in processing commands and sensor data. Reuse of execution level functions and data structures reduces the amount of unique code needed by the tactical level. A modular interface design permitted the departments and OOD to be developed simultaneously. Figure 8 shows interprocess communications (IPC) from OOD to strategic level, execution level and other tactical level processes (Leonhardt 96).

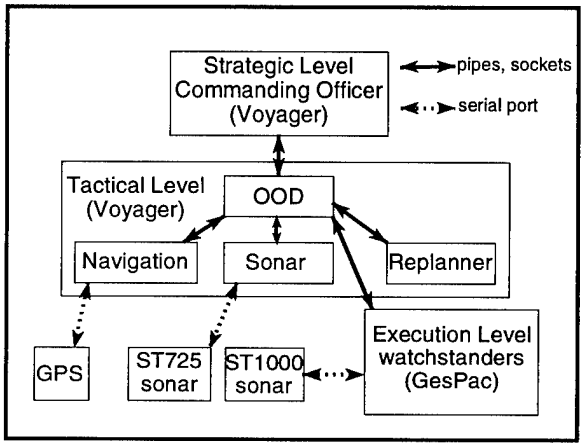


Figure 8. Interprocess communications (IPC) (Campbell 96).

Properly implementing IPC is crucial. Forked Unix processes have duplicate variable stores but do not share memory. Thus state variable changes in the parent (OOD) and children processes (navigation, sonar, replanner) must be performed individually for each process. We use standard Unix pipes for this communication since the tactical level is always within a single processor (Stevens 95). BSD-compliant sockets are used for communications to the execution level since that operates on a different processor (or even on a different network). Separate communication channels are used for updating state vectors and exchanging orders/ acknowledgements.

Navigation. The navigation module is a parallel forked process of the tactical level. It uses an Asynchronous Discrete Kalman Filter to filter GPS satellite navigation data received from a Motorola 8-channel GPS/DGPS unit and ranges received from a commercial short baseline sonar range system (DiveTracker).

The *Phoenix* is designed for precision navigation requiring position accuracy of 1 m. The standard deviation of the position available from GPS is approximately 60 m, with DGPS being accurate within 2 m. The DiveTracker short baseline acoustic ranges have a geometry-dependent standard deviation within 20 cm (with an occasional range out to 33 cm) which can cause a transiting position uncertainty of 1-3 m. Using raw positions results in fix-to-fix position uncertainty, control chattering and hydrodynamic stability problems for *Phoenix*. Kalman filtering corrects these difficulties.

Kalman filtering is a method for recursively updating an estimate of the state of a system by processing a succession of measurements. The *Phoenix* implementation uses a model-based movement estimator for state, combined with measurements, to produce the most probable estimate of the vehicle's position. A discrete Kalman filter is used to process measurements, and the use of acoustic range data requires an Extended Kalman Filter mode of operation due to the nonlinearity of range measurements (Bachmann 96).

Accurate and efficient navigation from point to point also requires the knowledge of the local ocean currents to prevent undershooting the intercept course towards the desired location. If a vehicle fix determines that the vehicle is not where the motion model predicts, then the likely causes are ocean current or AUV speed/heading errors. Using a non-zero mean movement model (where input vehicle speed is assumed truth) results in the filter solving for both an updated position data and estimates of ocean current. Estimated ocean currents are actually the combined sum of actual ocean current, errors in reported speed and heading errors. The ocean current values produced can thus change with the vehicle heading, but the root mean squared value of the currents will converge to a steady state number. This number can be resolved to X/Y or set/drift (polar) components for dead reckoning use. As with most processes at the tactical level, the algorithmic basis for this approach is similar to techniques used by human navigators.

By monitoring the difference between a motion model and measurements, the Kalman filter can determine if it has possibly lost track or received a bad measurement. If the difference is briefly too high, then the measurement is ignored. If the difference is too high for longer than 15 seconds, then it is assumed that the filter has lost track. Upon loss of track, the tactical level is informed and the OOD surfaces to gain a GPS fix and reset the filter state and parameters. This GPS-FIX procedure is designed to work equally well in hover and waypoint control. Full navigator details are in (McClarin 96) (Bachmann 96).

Real-time Sonar Classification. Real-time sonar classification and run-time collision avoidance are essential for AUV autonomy and survivability. An off-line sonar classification expert system was originally written using the CLIPS expert system shell (Brutzman 92b, 92c). Successful development of rules was originally dependent on the support of the expert system rule-matching engine. Once the expert system was developed, translation to C was practical and the optimized sonar classifier is now capable of running in real time to meet robot sensing requirements (Campbell 96).

The sonar module initializes sonar transducer parameters for maximum range scale, orientation change step size and transmitter power settings. Three modes are available: "transit search," "sonar search," and "rotate search." The transit search consists of a 60° sonar scan in front of the AUV. This search is primarily conducted for collision avoidance. The other two modes are conducted in a search area to detect, localize and classify any unknown objects. Sonar search and rotate search are 360° searches. Sonar search is performed by mechanically rotating the sonar head, whereas rotate search is accomplished with the sonar head fixed while the full *Phoenix* body performs a 360° rotation.

Sonar processing begins with filtering, thresholding and smoothing of the raw sonar data to produce a return bearing and range. The returns are then fitted to line segments using parametric regression. Line segments are started when a sliding window locates four returns that form an acceptable line. Points are subsequently added based on distance from the line segment and whether the new resultant line segment is acceptable. Completed line segments are then combined based on proximity and orientation.

To remove the directionality effects of sonar scan rotation, comparison of line segments is performed by first using the segment that is more clockwise relative to the AUV. Once objects and line segments are formed, heuristic rules are applied to classify the objects. The last part of the classification process is to relay object information in a manner suitable for path planning purposes. A circle representation is used with the center at the centroid of the object. Particularly long line segments (i.e. walls) are converted to a set of small adjacent circles. This methodology works. Additional experimental results are needed to ensure that system coefficients are properly tuned for current *Phoenix* sonars.

Imminent collision avoidance is achieved with a simple relative bearing and range check for all valid returns that contribute to any line segment. If a return does not contribute to a line segment it is not evaluated and is treated as a spurious return. We have developed more robust imminent collision avoidance algorithms independent of near-real-time sonar classification using the second steerable sonar. Using multiple noninterfering sonars permits employing search techniques that are otherwise mutually exclusive when sharing a single sonar transducer head. The collision avoidance sonar (usually the ST725) is directly controlled by the execution level for reliability and rapid response.

Path Planning and Replanning. Path planning is a tactical function. The strategic level contains the commanding officer (CO) and controls the overall mission plan. The CO decides (in general terms) where the ship will operate. Meanwhile, achieving the ordered track is the responsibility of the tactical level Officer of the Deck (OOD). To determine a safe route to the location the CO has requested, the OOD tells the tactical-level replanning department the desired location and the ship's present position. The sonar department (via the OOD) provides the replanning department with the current physical environment, i.e. where all the "circled" obstacles are. The replanning department takes this data and provides the OOD with the best path to the CO's ordered location after adding a safety distance around any obstacles. If a new obstacle is found by sonar while the ship is transiting, the OOD will call upon the replanning department to check the path. Replanning does not constantly process data but rather is called when the OOD needs it.

As a final step, smooth motion planning algorithms are applied to the output of the circle world path replanner in order to provide precise control of *Phoenix* and allow for rapid travel around obstacles without slowing into hover mode (Brutzman 92c) (Kanayama 95) (Leonhardt 96) (Davis 96a). Hover mode is inefficient when transiting waypoints, since it requires *Phoenix* to stop and maintain posture at a given location. Given the turning radius of a vehicle, smooth motion planning allows the vehicle to go from one point to another along a path that does not require the vehicle to perform instantaneous changes in direction. Thus the vehicle does not need to rotate in place when negotiating around obstacles. Replanner details are in (Leonhardt 96). Figure 9 illustrates the end-to-end process of detecting, classifying, localizing and avoiding a sonar obstacle.

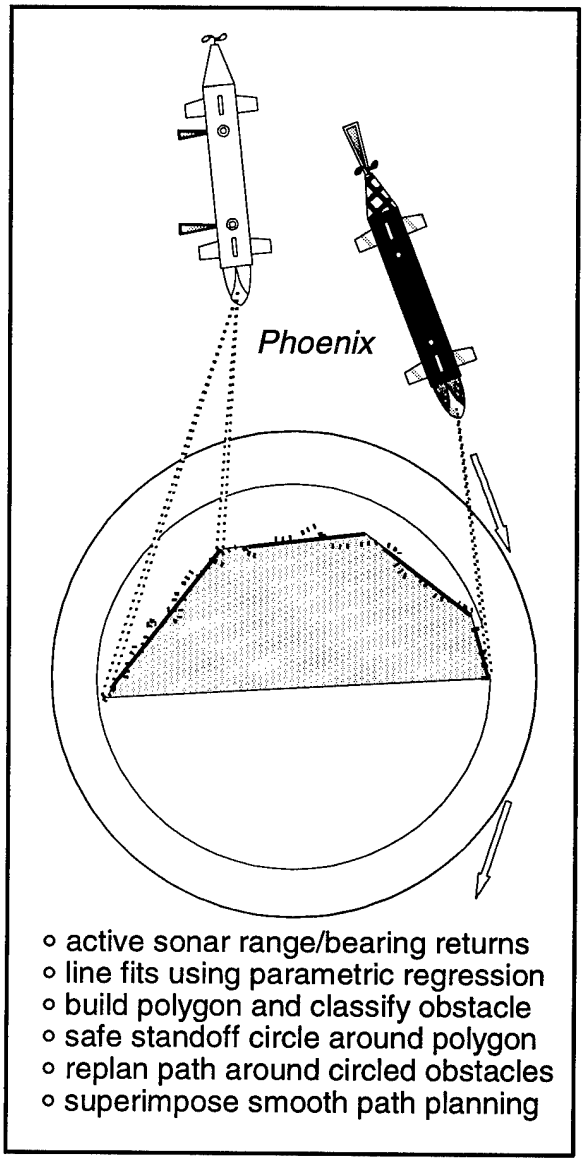


Figure 9. Obstacle detection, classification, localization and avoidance.

7 STRATEGIC LEVEL

Prolog. The RBM strategic level is typically written in Prolog, a language for predicate logic. The strategic level implements a planning capability by sequencing mission phases and backtracking when necessary to provide appropriate guidance to the tactical level as portions of the mission succeed or fail. Strategic level design criteria follow in Figure 10.

- Symbolic computation only, contains mission-independent doctrine predicates and current mission guidance predicates
- No storage of internal vehicle or external world state variables
- Rule-based implementation, incorporating rule set, inference engine and working memory (if required)
- Non-interruptible, not event driven
- Directs tactical level via asynchronous message passing
- Messages may be either commands or queries requiring Boolean responses
- Operates in discrete (Boolean) domain independently of clock time
- Building blocks: goals
- Abstraction mechanism: goal decomposition (backwards chaining) and rule partitioning (forward chaining); both are based on goal-driven reasoning

Figure 10. RBM characteristics for strategic level (Byrnes 96).

Manually produced early versions of the strategic level worked properly but became large and complex. Strategic level code was streamlined by separating mission-independent doctrine from mission-specific guidance. With practice the strategic level Prolog code is relatively simple to read, produce and run. An example strategic level mission follows in Figure 11, where TASK might be a combination of GPS fix, drop marker, radio report, return home, etc.

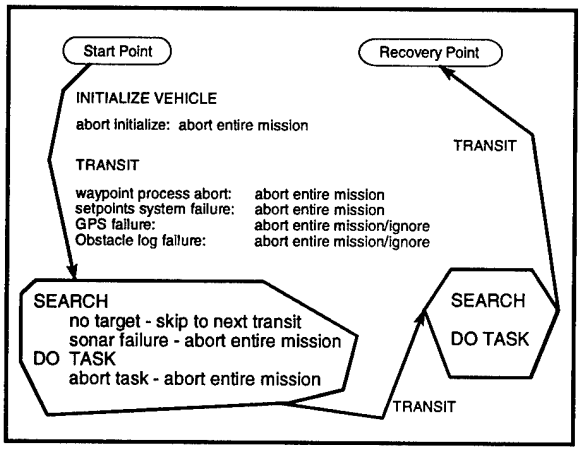


Figure 11. Strategic level representation of minefield search mission (Holden 95).

Mission Generation Expert System. The strategic level can also take the form of a deterministic finite automata (DFA). A mission controller initiates the phase associated with the current DFA node upon arrival, transitioning to a new node when the current node's phase completes successfully (or aborts because of a time out). A representative mission phase template appears in Figure 12. Individual tactic predecessors and successors can be composed using this template to create missions of arbitrary complexity (Davis 96a, 96b).

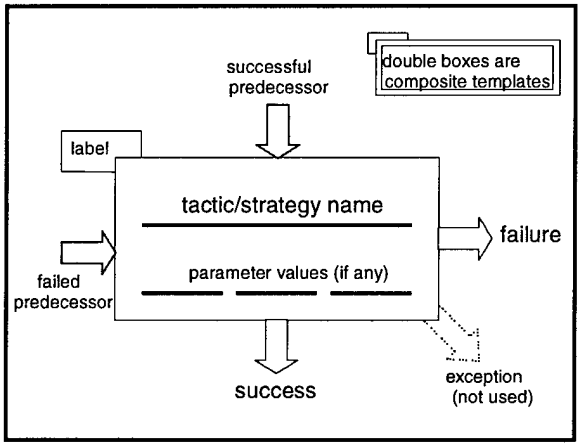


Figure 12. Template for tactic and strategy composition.

Advantages of the strategic level DFA structure are twofold. First, an arbitrary mission can be modeled simply as a set of phases that are executed in an order defined by the transitions of the DFA. Second, mission control using the Prolog search engine is powerful enough that complex behavior can be implemented without needing computationally intensive mathematical calculations. Arithmetic is confined to the tactical level, conceptual mission planning is confined to the strategic level.

Since a prime motivation for *Phoenix* is shallow water counter-mine operations, the mission generation process must be substantially simpler than writing Prolog programs if typical human operators are to deploy the AUV. One solution to this problem combines a graphical user interface for mission planning and specification together with a goal-driven expert system for strategic level code generation.

There are three aspects to the AUV Mission Generation Expert System. The first is a mission planning tool, which specifies vehicle launch and recovery positions and what the mission is supposed to accomplish. Means-ends analysis then computes a sequence of phases which can accomplish the desired mission. Failure of any single phase will cause a mission to either abort or follow an alternate failure-recovery phase (Byrnes 96). Since there may be multiple phase sequence solutions for a mission, each solution generated by the system is the next solution found as opposed to an optimal solution. In addition, missions generated through means-ends analysis are linear and proceed phase-by-phase to the end. In any case, users are allowed to choose among the candidate solutions generated (Davis 96a, 96b).

More complicated missions can take full advantage of this strategic level DFA structure. They are specified phase-by-phase using the second piece of the Mission Generation Expert System, the mission specification tool. This tool allows an experienced user who understands the DFA structure of the strategic level to define missions one phase at a time. Regardless of whether the mission planning tool or the mission specification tool is used, the system automatically checks input for correctness and logic and will not allow specification of an invalid mission (Leonhardt 96) (Holden 95) (Davis 96a, 96b).

The final aspect of this system is the code generation facility. By using specified phases, either the mission planning or mission specification tool, and templates for valid phase types (e.g. hover, search etc.) the system can generate executable code in either Prolog or C++. Earlier theses demonstrated that the strategic level can be equivalently instantiated using either the Prolog backwards chaining engine or the CLIPS forward chaining engine. Alternate languages are possible because there are multiple ways to plan. Backwards chaining can be unambiguously implemented using forward chaining, forward chaining can be unambiguously implemented using backwards chaining, and both can be implemented using fully enumerated decision graphs. Use of C++ has become possible because improved understanding and tighter constraints on mission primitives has eliminated the need for the full functionality of the Prolog search engine. Nevertheless such simplifications were only possible following extended experimentation using Prolog code.

Extensive testing of autogenerated Prolog and C++ code has been conducted in the virtual world, and successful in-water testing has been conducted at the *Phoenix* AUV test tank, Moss Landing Harbor and the NPS swimming pool. Further in-water tests are planned. Accomplishing our goal of simplifying mission generation is indicated by a significant reduction in the time required for mission coding (minutes when using the expert system as opposed to hours without it). Finally, syntactic programming errors have been completely eliminated by the source code autogeneration system and logical programming errors have been substantially reduced.

8 ROBOT NETWORKING

Perhaps surprisingly for a small robot, networking is a major consideration. Within the *Phoenix* AUV is an Internet-connectable local-area network (LAN). This enables network communications between and within the three software levels, external connectivity in laboratory via tether cable, and (optionally) external connectivity during harbor testing. Remote connection of the LAN to the campus Internet backbone is achieved using multiple wireless bridge boxes. Multicast Backbone (MBone) connectivity permits local or world-wide transmission of audio, video and DIS streams (Macedonia 94). World Wide Web links to online software documentation, multiple research group accounts and properly networked LANs with group access around campus further strengthened this software development collaboration. Ease of use and remote access translate into significant productivity gains and regular discovery of new capabilities. We expect to someday extend this approach underwater by developing Internet Protocol over Sea Water (IP/SW) connectivity (Brutzman 95a). Other network considerations are elaborated in Section 11 as part of virtual world connectivity.

9 VIRTUAL WORLD

The harsh environment in which an AUV must operate calls for extra precautions in its design to prevent damage to or loss of the vehicle. We have developed a medium-scale virtual environment which enables meaningful end-to-end testing of robot software and hardware in the laboratory (Figure 13). As noted in earlier work on the virtual world:

> It is tremendously difficult to observe, communicate with and test underwater robots, because they operate in a remote and hazardous environment where physical dynamics and sensing modalities are counterintuitive. An underwater virtual world can comprehensively model all necessary functional characteristics of the real world in real time. This virtual world is designed from the perspective of the robot, enabling realistic AUV evaluation and testing in the laboratory. 3D real-time graphics are our window into the virtual world, enabling multiple observers to visualize complex interactions. A networked architecture enables multiple world components to operate collectively in real time, and also permits world-wide observation and collaboration with other scientists interested in the robot and virtual world. (Brutzman 94)

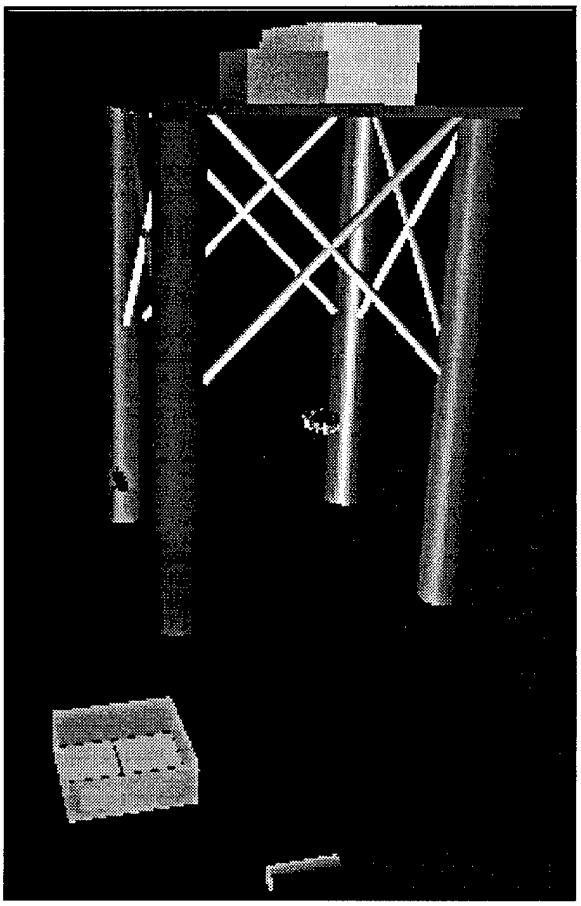


Figure 13. Underwater virtual world for an AUV (Brutzman 94).

The objective of the underwater virtual world is to reproduce real-world robot behavior with complete fidelity in the laboratory. Many questions pertain. What is the software architecture required to build an underwater virtual world for an autonomous underwater vehicle? How can an underwater robot be connected to a virtual world so seamlessly that operation in the real world or a virtual world is transparent to the robot? How can 3D real-time interactive computer graphics support wide-scale general access to virtual worlds? Specifically, how can computer graphics be used to build windows into an underwater virtual world that are responsive, accurate, distributable, represent objects in openly standardized formats, and provide portability to multiple computer architectures? Overview answers to these questions are provided here. Detailed analyses and example solutions are presented in (Brutzman 94). In effect, the virtual world requires a separate software architecture for networked world models that complements the robot software architecture.

The real world is a big place. Virtual worlds must similarly be comprehensive and diverse if they are to

permit credible reproductions of real-world behavior. A variety of software components have been shown necessary. In every case, 3D real-time visualization has been a crucial tool in developing AUV software. Ways to scale up and arbitrarily extend the underwater virtual world to include very large numbers of users, models and information resources are also incorporated in this work.

Virtual world capabilities were utilized for testing and verification throughout the software development process. Use of this tool allows a number of programmers to work independently and in concert. Virtual world capabilities have been incrementally improved to match increased vehicle software capabilities, such as hydrodynamics and controller response rendering (Figure 14). Scientific visualization techniques have provided further significant benefits (Brutzman 95b).

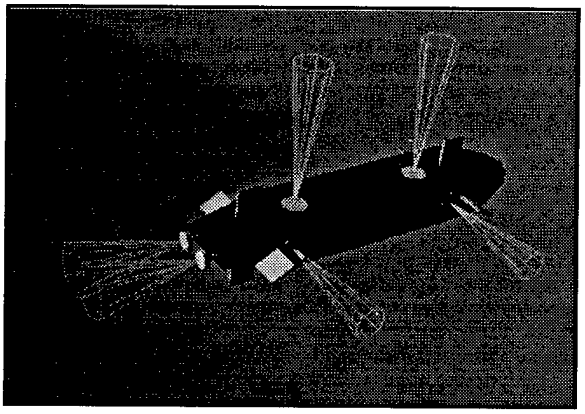


Figure 14. Detailed hydrodynamics and control visualization is essential.

10 VISUALIZING CONTROL ALGORITHMS

Designing an AUV is complex. Many capabilities are required for an underwater mobile robot to act capably and independently. Stable physical control, motion control, sensing, path planning, mission planning, replanning and failure recovery are example software components that must be solved individually for tractability. The diversity and dissimilarity of these many component subproblems precludes use of a single monolithic solution paradigm.

Vehicle control algorithms are implemented using either thrusters (hovering modes), planes/rudders/ propellers (cruise modes) or all effectors in combination. Control algorithms for the following behaviors are included: depth control, heading control, open-loop rotation, open-loop lateral motion, waypoint following and hovering. Control algorithms are permitted to operate both thrusters and planes/rudders/propellers simultaneously when such operation does not provoke mutual interference. Most *Phoenix* control code has been developed and tested in conjunction with the construction of a real-time six degree-of-freedom hydrodynamics model. Design, tuning and optimization of control algorithms in isolation and in concert is the subject of active research (Healey 93, 96) (Fossen 94) (Marco 96a) and remains an important area for future work. Control algorithm robustness is a particularly important topic since potentially fatal nonlinear instabilities are possible and vehicle reliability is paramount.

Typical efforts at hydrodynamic development are based on mental interpretation of multiple time-series such as Figure 15. Dozens of two-dimensional time-series plots are necessary for quantitative performance analysis, but this approach remains notoriously difficult to use when attempting to mentally integrate and visualize all aspects of vehicle behavior. The successes of individual control algorithms created as part of this effort were highly dependent on 2D and 3D visualization techniques. Complete derivations of the full hydrodynamics model and corresponding control equations are in (Brutzman 94, 96c).

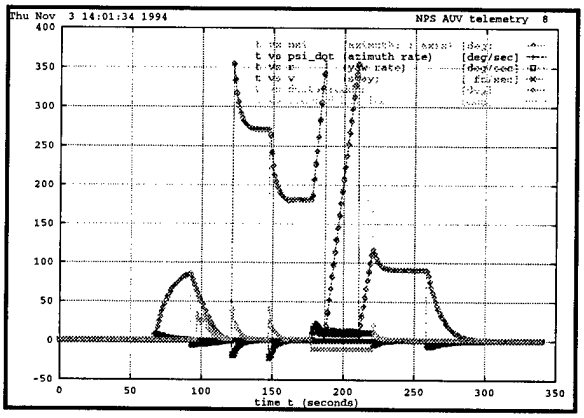


Figure 15. Representative time-series behavior plot.

An example challenging scenario for an AUV is evaluating vehicle control stability when transitioning from stable submerged control to intentional surface broaching in Figures 16 and 17. This scenario exercises the real-time buoyancy model developed in (Bacon 95). Real-time 3D observation of such scenes is an essential tool when developing and testing algorithmic models.

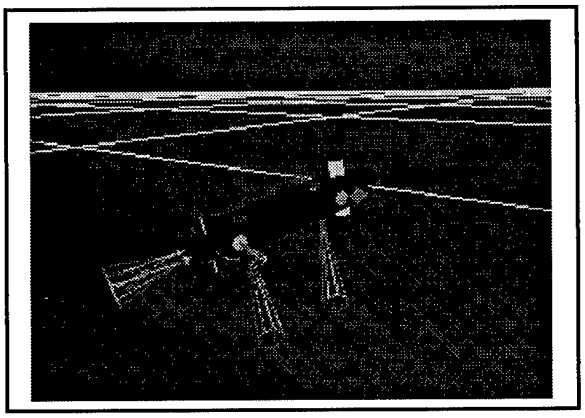


Figure 16. Evaluating control response while broaching.

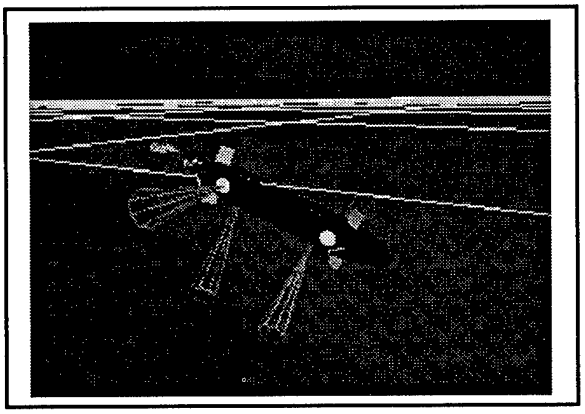


Figure 17. Evaluating control response after broaching.

11 AUV-VIRTUAL WORLD COMMUNICATIONS

Since RBM is a multilevel architecture, communications between levels must be formally defined. Communications between robot and virtual world must also be clearly specified. Defining communications includes establishing a physical path for data transfer as well as defining the syntax and protocol of exchanged messages. Our design objectives include reliability and clarity so that messages are easily created and easily understood, either by software processes or by people. Details follow in order to illustrate the precise relationships between robot, virtual world and graphics-based user viewing windows.

Two kinds of messages are defined for use between robot and virtual world. The first is the telemetry vector, which is a list of all vehicle state variables pertinent to hydrodynamic and sensor control. Telemetry vectors are passed as a string type. The second kind of messages allowed are free-format commands. Free-format command messages are also string types, starting with a predefined keyword and followed by entries which may optionally have significance depending on the initial keyword. Messages with unrecognized keywords are treated as comments. These two kinds of messages (telemetry and commands) can be used for any communication necessary among robot-related entities. Employment of string types facilitates data transfer between different architectures, data transfer via network sockets, and file storage. String types also ensure that all communications are readable by both robot and human, a trait that is particularly useful during debugging. An open format for command messages permits any user or new application to communicate with little difficulty.

Within the AUV, the basic communications flow between execution level and tactical level is straightforward. All telemetry vectors are sent from the execution level to the tactical level, providing a steady stream of time-sensitive, rapidly updated information. The tactical level may send commands to the execution level as desired, and the execution level may return informational messages between telemetry vectors as appropriate. Nonadaptive tactical level functionality can also be provided by carrying out prescripted mission command files. Telemetry vector records and command messages are logged in separate mission output files for post-mission analysis and replay.

The telemetry vector serves several essential purposes. In addition to providing a steady stream of information from the execution level to the tactical level, the telemetry vector also serves as the data transfer mechanism between execution level and virtual world. Efficient communications between robot and virtual world are essential if rapid real-time 10 Hz robot response is to be maintained. The telemetry record is a concise and complete way to support all of these data communications requirements. Figure 18 shows in detail how the flow of control proceeds and the telemetry vector is modified during each *sense-decide-act* cycle.

Robot execution software is designed to operate both in the virtual world and in the real world. While sensing in the virtual world, distributed hydrodynamics and sonar models fill in pertinent telemetry vector slots. While sensing in the real world, actual sensors and their corresponding interfaces fill in pertinent telemetry vector slots. In either case, the remainder of the robot execution program which deals with tactical communications, command parsing, dynamic control, interpretation etc. is unaffected. While operating in the virtual world, robot propulsion and sensor commands are communicated via the same telemetry vector. While operating in the real world, robot

propulsion and sensor commands are sent directly to hardware interfaces for propellers, thrusters, planes, rudders, sonar steering motors, etc. Again almost all parts of the robot execution program are completely unaffected by this difference. This networked architecture is essentially transparent to the robot, permitting identical AUV operation in the real world or virtual world.

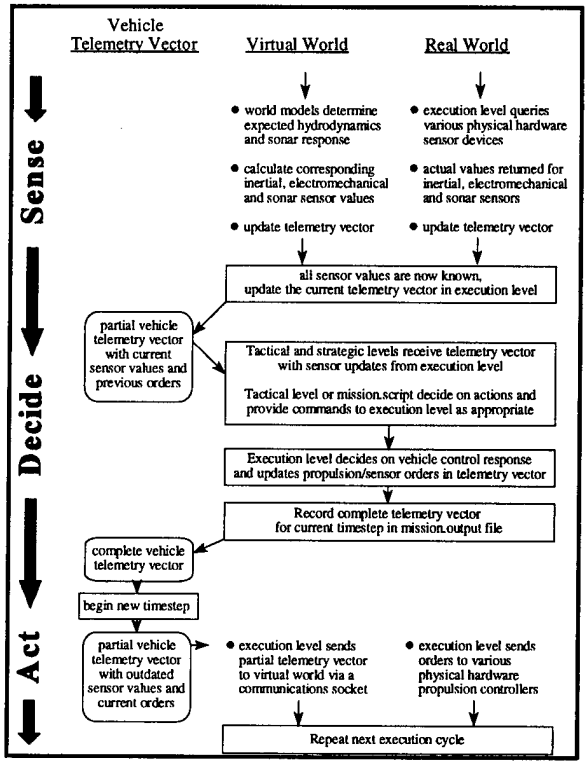


Figure 18. Data flow via the telemetry vector during each *sense-decide-act* cycle.

The telemetry vector is therefore a key data transfer mechanism. Telemetry vector updates also define the communication protocol between execution level and virtual world. As might be expected, this works well because the execution level program follows the common robotics cyclic paradigm of *sense-decide-act*. Figure 19 provides an overview of the telemetry vector update sequence as an alternate means of portraying the validity of this approach. Given the perhaps-worst-case computational complexity of underwater world models, this networked virtual world software architecture for real-time performance in the laboratory also appears applicable to other robot domains.

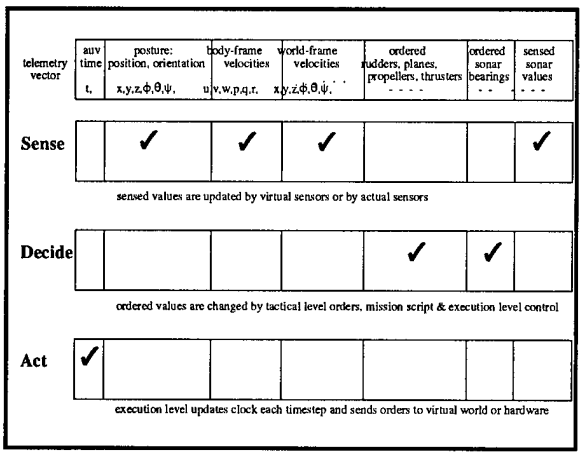


Figure 19. Telemetry vector modifications during each *sense-decide-act* cycle.

12 INTERACTIVE 3D GRAPHICS

Several important requirements are needed for the creation of object-oriented graphics viewers for visualizing a large-scale virtual world. Open standards, portability and versatility are emphasized over platform-specific performance considerations in order to support scaling up to very large numbers of users, platform types and information sources. The *OpenInventor* graphics toolkit and scene description language has all of the functionality needed. The potential integration of network connections to logically extend graphics programs is also examined. Open standards, portability and versatility are emphasized over platform-specific performance considerations in order to support scaling up to very large numbers of users, platform types and information sources.

A good graphics toolkit for building a virtual world viewer has many requirements to fill (Foley, van Dam 90). Rendered scenes need to be realistic, rapidly rendered, permit user interaction, and capable of running on both low end and high end workstations. Graphics programmers must have a wide range of tools to permit interactive experimentation and scientific visualization of real-world datasets (Thalmann 90). The ability to read multiple data formats is also important when using scientific and oceanographic datasets. Scientific data format compatibility can be provided by a number of data function libraries which are open, portable, reasonably well standardized and usually independent of graphics tools (Fortner 92). Viewer programs need to be capable of examining high-bandwidth information streams and large archived scientific databases. Thus the ability to preprocess massive datasets into useful, storable, retrievable graphics objects will be particularly important as we attempt to

scale up to meet the sophistication and detail of the real world. Adequate standardization of computer graphics and portability across other platforms is also desirable but has been historically elusive.

OpenInventor is an object-oriented 3D graphics toolkit for graphics applications design (Strauss 92). Based on the *Open GL* graphics library, *OpenInventor* provides high-level extensions to the ***C++*** (or ***C***) programming language and a scene description language. It is designed to permit graphics programmers to focus on what to draw rather that how to draw it, creating scene objects that are collected in a scene database for viewpoint-independent rendering.

The ability to store graphics objects as readable, editable files is especially appealing for the creation of large-scale virtual worlds. Since the performance of computer graphics is highly dependent on the computational complexity of scenes to be rendered, it is inevitable that truly large-scale world scene databases will eventually overload viewing graphics workstations. Such overload will occur regardless of the efficiency of viewpoint culling algorithms and graphics pipeline optimizations, unless partitionable and networked scene databases are used. Furthermore, since populating a virtual world is a task that needs to be open and accessible to large numbers of people, an open graphics data standard is needed for virtual world construction. The ability to selectively load graphics objects and scenes from files is an important distribution mechanism which can take advantage of Web connectivity.

Ubiquitous portability for analytic, hypermedia, network, multicast and graphics tools is therefore an essential feature for virtual world model builders. A superior alternative is now available using the Virtual Reality Modeling Language (VRML) specification (Carey 96). VRML is the Web standard for interactive 3D representation. VRML scene description files are the best approach for object definitions in a large-scale virtual world (Brutzman 96d).

13 SONAR VISUALIZATION

Sensor differences distinguish underwater robots from ground, air and space-based robots. Since the oceans are generally opaque to visible light at moderate-to-long ranges, vision-based video systems are ordinarily of use only at short distances and are unreliable in turbid water. Vision systems also usually require intense light sources which deplete precious energy reserves. In comparison to underwater computer vision, active and passive sonar (acoustic detection) has long been a preferred sensing method due to the long propagation ranges of sound waves underwater.

However, sound waves can be bent by variations in depth, temperature and salinity. A variety of problems including ambient noise, multipath arrival, fading, shadow layers, masking and other effects can make sonar use difficult. Since active sonar typically provides good range values with approximate bearing values, algorithms for sonar recognition are much different than vision algorithms. In the short sonar ranges used by *Phoenix*, simple error probabilities and linear geometric sonar relationships are adequate. Figure 20 shows the perspective gained by observing AUV sonar from an "over the shoulder" perspective, one of several vantage points needed when developing sonar classification algorithms.

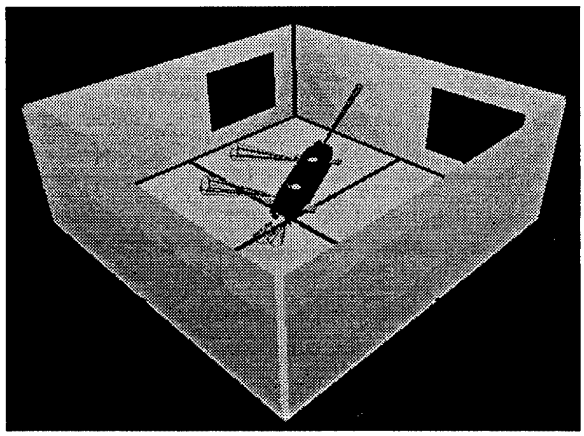


Figure 20. Local viewpoint of active sonar in test tank.

Since sonar is the most effective detection sensor used by underwater vehicles, sonar visualization is particularly important when designing and evaluating robot software. Sonar parameters pertinent to visualization and rendering include sound speed profile (SSP), highly-variable sound wave path propagation, and sound pressure level (SPL) attenuation. Several questions are prominent. How can a general sonar model be networked to provide real-time response despite high computational complexity? How can scientific visualization techniques be applied to outputs of the sonar model to render numerous interacting physical effects varying in three spatial dimensions and time? Initial investigations indicate that this area may yield significant results. The high dimensionality of sonar data is best served by scientific visualization techniques.

Sonar sensing is crucially important (Stewart 92). Previously only a single geometric sonar model was available for *Phoenix*, derived by hand to model the AUV test tank (Figure 21). Although effective in a small regular volume, this approach was too limited and did not permit easy addition of artificial targets or

obstacles. We adapted the computational geometry routines included in the *OpenInventor* interactive 3D graphics library to shoot rays into the scene database to produce a general geometric sonar model. Now the same scene database (made up of *OpenInventor* and VRML files) can be used for both virtual world visualization and real-time 3D sonar ray intersection calculations (Figure 22) (Davis 96a) (Brutzman 96b).

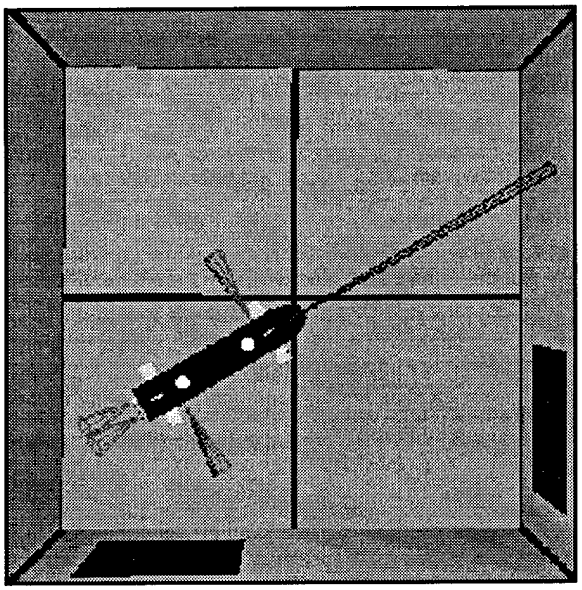


Figure 21. Manually derived geometric sonar model for AUV test tank (Brutzman 94).

14 EXPERIMENTAL TEST RESULTS

Once *Phoenix* functionality was correct in the virtual world, test tank experiments were conducted to fine tune hardware and properly move the AUV through the water. Diving, forward, backward, lateral and rotational movement checks were all performed during these test tank experiments. However, the calibration of speeds during these movements could not be tested due to the relatively small size of the test tank (6m x 6m x 2m deep).

The next vehicle tests were performed in the relatively calm sea water harbor in Moss Landing California. A variety of logistical problems were overcome but a seemingly endless series of minor hardware failures then thwarted each attempt to run a complete minefield search. Although a complete mission was never accomplished beginning to end, all components of the mission were individually exercised. We now believe that the functionality and logic of the AUV software is correct (Brutzman 96b). Remaining tests include repeated mission testing, verification of aggregate software behavior under a variety of scenarios, tuning of control constants, and validation of both hydrodynamics and sonar models in the virtual world. Recent results include precise vehicle maneuvering and rendezvous with a docking tube (Davis 96a, 96b) (Figure 23). Much more experimental testing awaits.

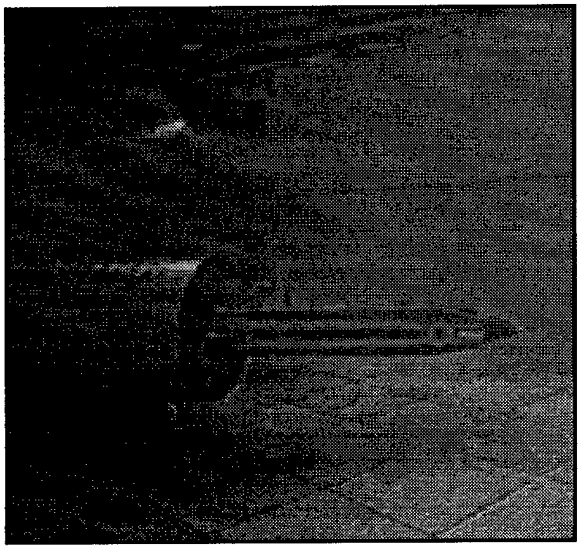


Figure 22. *Phoenix* AUV maneuvering to enter a docking tube using onboard sonar (Davis 96a, 96b).

15 FUTURE WORK

An underwater vehicle which can transit through waypoints and hover in the presence of currents enables a variety of capabilities which are not possible for vehicles that must retain forward way to remain hydrodynamically stable. We intend to examine whether the *Phoenix* hull form can stably approach and neutralize a moored mine-like object. Figure 24 is a notional diagram that shows how sonar can be used to carefully approach a target broadside, keep station against the ocean current, take confirming video, and attach a beacon or neutralizing device using a simple one- or two-degree-of-freedom effector. For low sea states, we see few limiting factors in this approach.

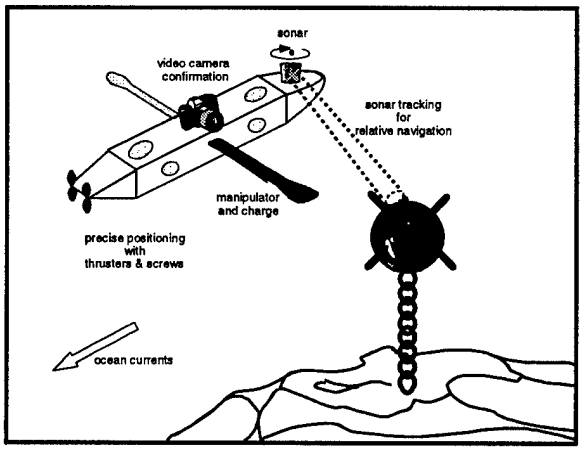


Figure 23. A mobile stable AUV might precisely place an explosive charge on an underwater mine.

Phoenix is only directly controllable in five degrees of freedom since roll is unconstrained. Pitch stabilization is straightforward using vertical thrusters. Testing will determine whether roll stabilization is also necessary, perhaps by using an additional thruster. We are further interested in development of automatic diagnostics that reconfigure control algorithms to handle equipment faults. We also intend to explore local measurement of cross-body ocean current flow using acoustic doppler current profilers (ADCPs), in order to permit precise maneuvering in the midst of highly varying flow fields and high sea states. Finally, future work on underwater virtual world networked graphics includes compatibility with common Web browsers using the Virtual Reality Modeling Language (VRML) (Brutzman 96d).

16 CONCLUSIONS

The underwater environment is extremely challenging for robots. Counterintuitive hydrodynamics response, poor visual capabilities, complex sonar interactions, communications inaccessibility and power endurance are significant design constraints. Robot builders must provide stable control and reliable operation at all times due to the unacceptably high cost of failure. A variety of AI processes must be used for planning, sensing and other complex tasks.

Systems integration is significant due to the many sensors and effectors required for nontrivial operation. The *Phoenix* AUV demonstrates that a three-layer robot architecture can be effective at combined system control over time scales ranging from hard-real-time sense-decide-act response to temporally unconstrained mission planning.

Using an underwater virtual world for interactive 3D graphics rendering is an essential capability for effective AUV development. The networked software architecture and various results described here demonstrate that a real-time physically based underwater virtual world is feasible. It enables repeated testing of all aspects of underwater vehicle control, stability, sensing, autonomy and reliability. Graphics viewer requirements include scientific visualization and portability across multiple platforms. The use of multicast DIS messages, Web access and VRML scene descriptions that include dynamic behaviors promise the possibility of scaling to very large numbers of participants. Network connectivity allows us to use the global Internet as a direct extension of our desktop computers, permitting global collaboration on a routine basis.

After years of effort, the RBM architecture is fully instantiated onboard the *Phoenix* AUV and is being successfully tested and refined by in-water testing. A networked underwater virtual world has been crucial to this development project. Experimental results indicate we are close to demonstrating that affordable underwater robots can operate autonomously in challenging environments.

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18 SOFTWARE AND DOCUMENTATION

All source code, support files and compiled executable programs are available via the Internet (Brutzman 96a). This software reference includes help files, *Phoenix* software, 3D graphics viewer, hydrodynamics, sonar modeling, networking and Multicast Backbone (MBone) resources. AUV dynamics software is parameterizable for other vehicles and all work is in the public domain. Available at *http://www.stl.nps.navy.mil/~auv*

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A Small Co-Axial Robotic Helicopter for Autonomous Mine-Field Search and Destroy Missions

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I. INTRODUCTION

According to an article in the May 1996 issue of Scientific American magazine, "Land mines kill or maim more than 15,000 people each year. Most victims are innocent civilians. Many are children. Still, mines are planted by the thousands everyday"

I have been following the progress of mine detection and demining procedures for about 4 years. I am very disappointed at the lack of progress that has been made in this field.

About 2 years ago, in 1994, I decided to do something about this situation. The United States has sent humans to the moon and back and has sent robots to Mars and beyond. There are all kinds of technologies available out there, to help solve the mine detection and removal problems, but there were several key technologies that were missing or just "not there yet."

Then, there was the question of money to pay for the R & D (which I will discuss later).

I have worked in Silicon Valley for 25 years and I knew where to find most of the high-tech components of a mine identification and locating system...and the people who could put it together. What was missing were 4 key elements:

1. The Vehicle to carry the equipment...a vehicle that can fly 5 to 40 feet high at 5-10 miles per hour.

2. A very sensitive Magnetometer to detect the mines...one that was available in a small, lightweight package.

3. High precision GPS to guide the vehicle.

4. The Funds to pay for the development of the system.

A closer look at each of the 4 missing element reveals the following:

1. The Vehicle:

What is needed is an anti-gravity machine that will carry about 25 pounds of payload.

Small helicopters at first seemed to be the answer.

We bought some off-the-shelf-hobby-type units and found that they were not nearly robust enough for this task. Also, they did not have the payload capacity needed.

We then designed and built a larger conventional helicopter (with a tail rotor) (see figures 1 to 4) and by now it was evident that standard helicopters like this have too many parts and too many adjustments. They have very poor stability and it requires about 200 hours to learn to fly..like balancing a tennis ball on a basketball.

So I then personally designed an entirely new concept in a helicopter-like vehicle. (See figures 5 to 7)

It has many desirable features:

- •No adjustments
- •Counter rotation blades
- •No tail rotor
- •Very low cost
- •Very small for payload achievable
- •Very low maintenance required

Then I had a friend design a very small, lightweight, low power, state-of-the-art inertial stabilization system using gyros and a solid state accelerometers that make the vehicle inherently stable.

We then located a company called Geometrics that makes very sensitive, and very lightweight cesium Magnetometers.

This Geometrics unit is the most sensitive type Magnetometer available, and can detect most buried land mines.

We are designing an on-board computer system to manage the vehicle's autonomous operation.

It Uses 20 mips embedded computer that is the size of a credit card.

- It uses fuzzy logic to make decisions on its own.

•The airborne system is autonomous which means you tell it what to do and it goes and does it... with no further contact needed from the ground.

•You can uplink a script file from the ground control laptop to the airborne vehicle and it goes and does it's prescribed maneuvers unless you override it with a command given from the ground.

That brings us to number 3 on the list of missing elements.

3. GPS system:

The Global positioning system uses 24 satellites. In 1994, the best accuracy a GPS receiver could give you was about 6 meters.

This was not good enough. We need accuracy of less than 10cm to be able to pinpoint the position of a mine and then come back and dig it up , destroy it in place , or carry it away.

Most people are under the false impression that GPS is only accurate to 30 meters. Now, with the latest differential GPS systems available, the accuracy is down to 2 cm.

•The price is now a great deal lower now.

•The size and weight are much less now.

So now an off-the-shelf GPS system is available that meets the requirements of this project.

The last missing element was the money to pay for the R&D for this project..

This is THE BIG PROBLEM. We have tried numerous money raising efforts:

• We have written a business plan for the project.

•We have distributed about 50 of the business plans.

• Nobody, no institutions, no government agency, no venture capitalist...nobody was willing to even consider this project. "Land mines are not a very sexy subject" and additionally, unless your business plan has the word "Internet" in it every two paragraphs, forget it with any venture capitalists.

So, I bit the bullet and financed this whole R&D project my self myself with my VISA gold cards. My own personal VISA cards are now maxed out at $100,000.

Look at the progress I have made on this project with only $100,000 invested so far...

(Giant companies like Lockheed and Boeing would have spent 10 million dollars by now to get this far on a project like this)

I feel it is time to give something back to the world...

With 100 million indiscriminate -killing-machines (buried mines) in place in the world and 1500 people..mainly children.. being maimed and killed each month.. something needs to be done and the US government (or any government) is not doing their part to help this situation.

The only US government funded demining research that I know of is the project at Fort Belvoir called the "Humanitarian Demining Program". It is being run by Harry N. (Hap) Hambric. Hap and his crew are doing a fantastic job with the limited funding they have available. What is needed is additional funding for Hap's organization. Then possibly there would be funding available to continue my co-axial robotic helicopter project. Hap Hambric can be reached at 703.704.1086. Here is what you can do to help make a difference: Call your Congressperson and explain that more funding is needed to combat this terrible buried mine problem.

2. Conclusion

The good news is we have an answer to the problem with our Robotic Helicopter... the bad news is that it is only 75% completed and I have maxed out my Visa cards so development has stopped.

So I come here today to ask for help in finishing this project.

We need: Strategic Relationship Partners and Funding to finish the R&D on the Project.

If you have access to a budget that can support this project or know of one, please contact me at 415.941.9090

Thanks for your help.

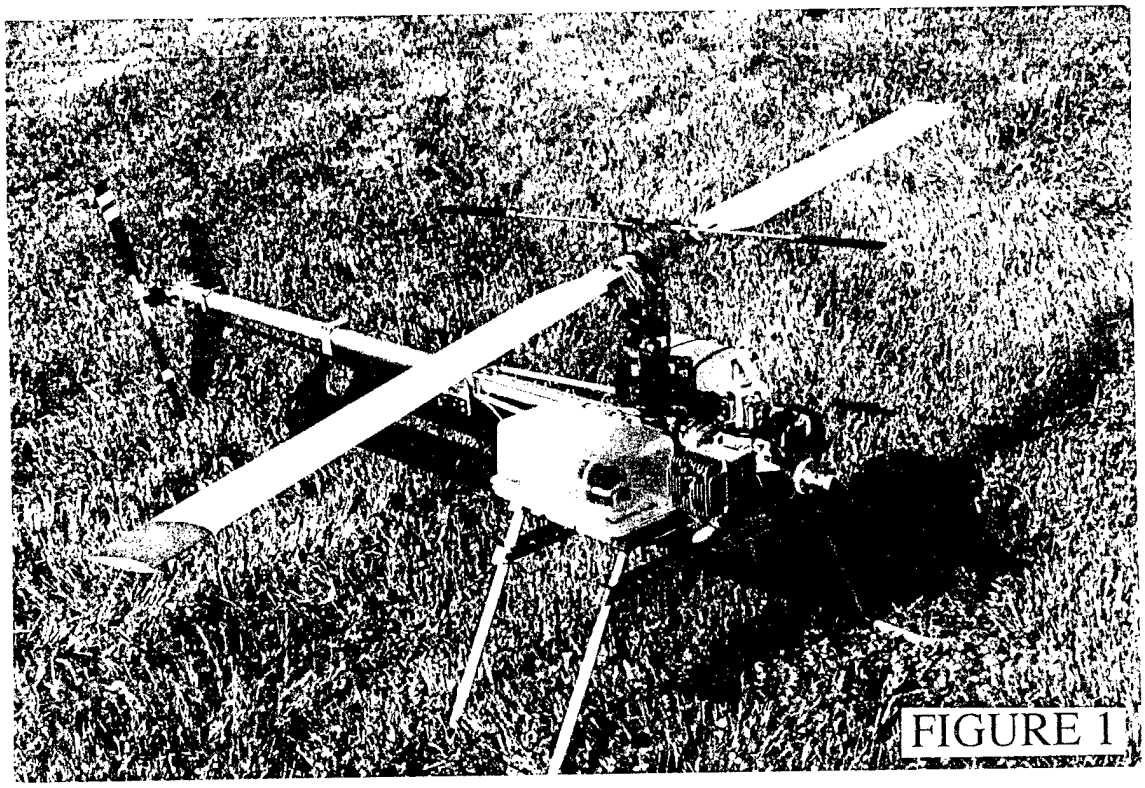


FIGURE 1

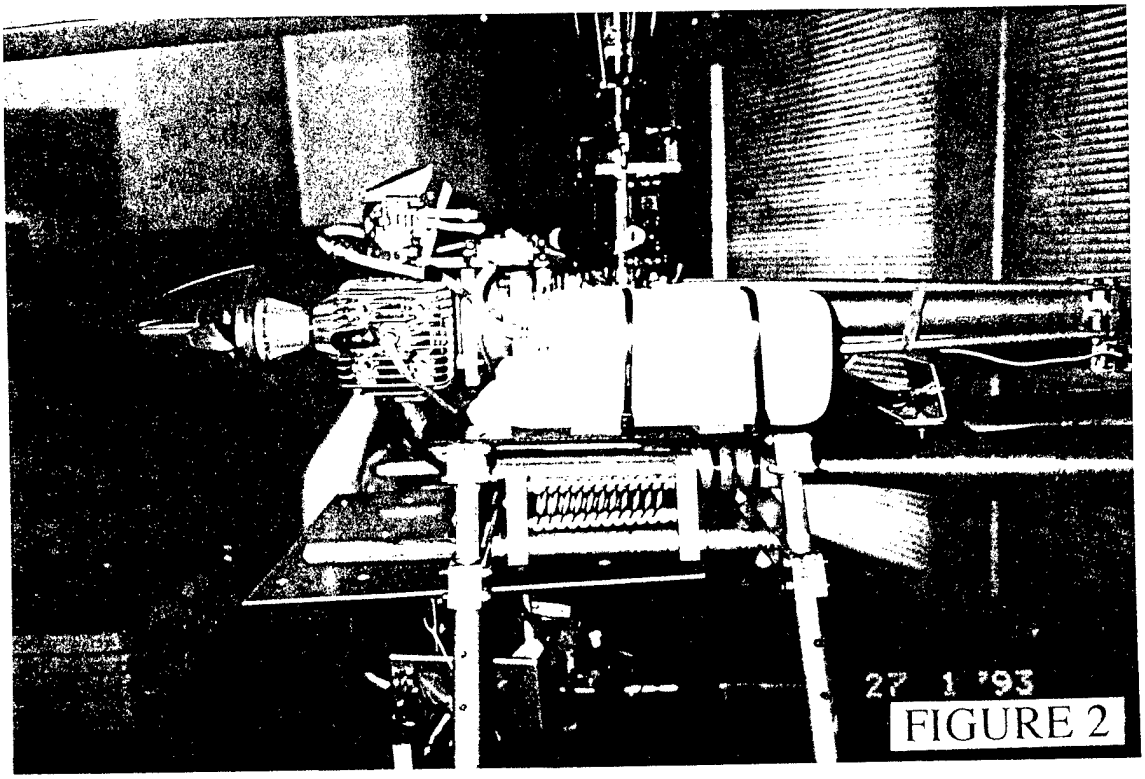


FIGURE 2

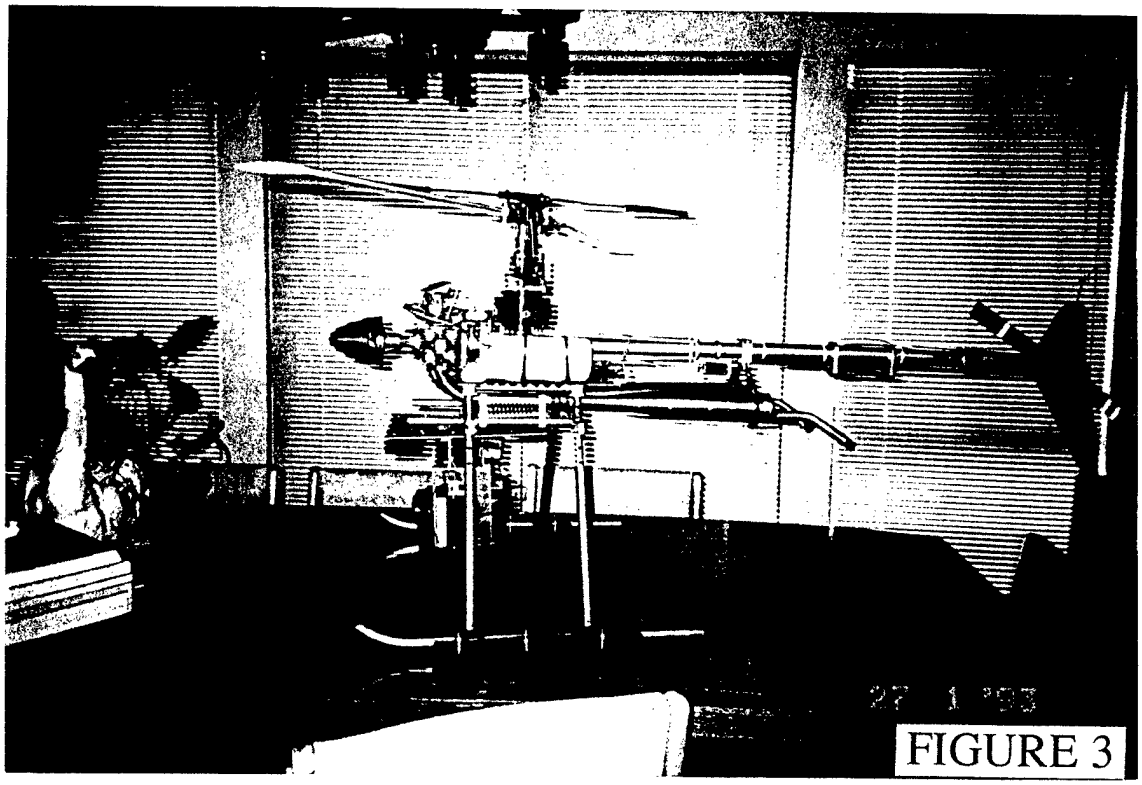


FIGURE 3

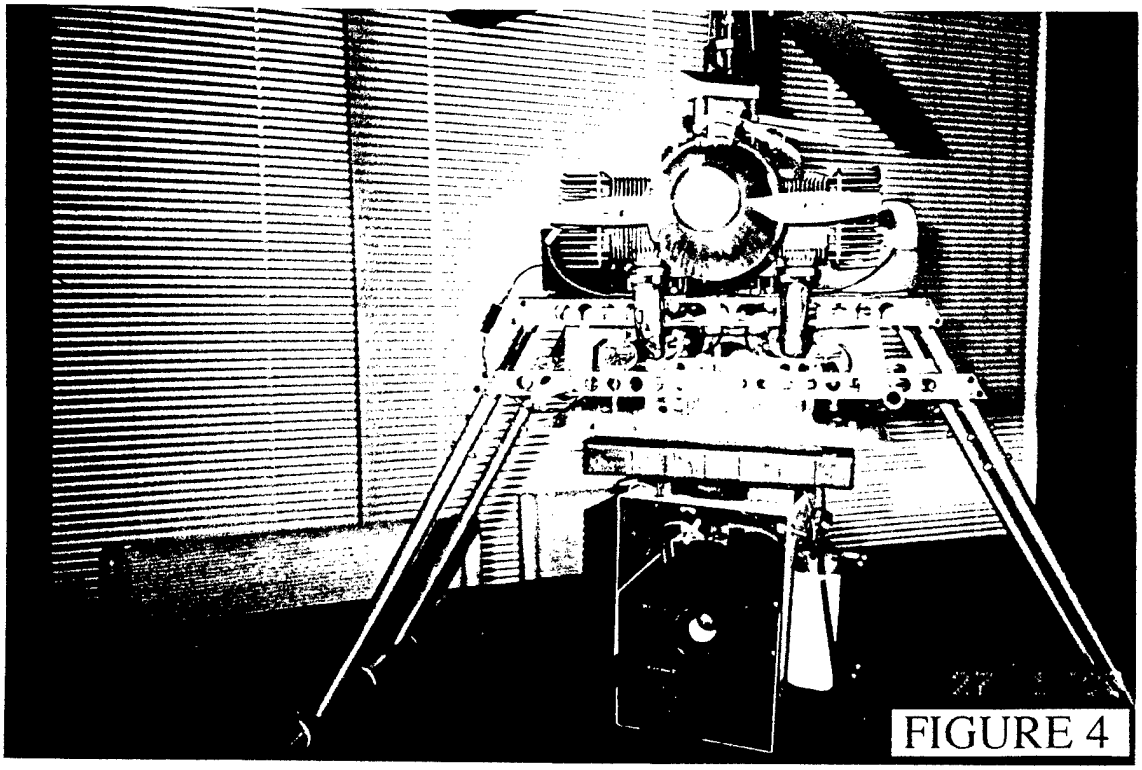


FIGURE 4

COLBY CO-AXIAL HELICOPTER

PRELIMINARY SPECIFICATION HIGHLIGHTS

- **RADICAL NEW DESIGN**
- **VERY SIMPLE CONSTRUCTION**
- **VERY LOW COST**
- **COUNTER-ROTATING BLADES**
- **LOW MAINTENANCE**
- **NO TAIL ROTOR**
- **NO COMPLEX CONVENTIONAL HELICOPTER LINKAGES**
- **NO CONVENTIONAL HELICOPTER MANUFACTURING OR MAINTENANCE PROBLEMS**
- **SMALL SIZE (4 UNITS FIT IN THE BACK OF A PICK-UP TRUCK)**
- **25 POUND PAYLOAD**
- **ON-BOARD GPS NAVIGATION SYSTEM**
- **ON-BOARD OPTIONAL COLOR CAMERA WITH RF DOWNLINK**
- **ON-BOARD OPTIONAL INFRA-RED CAMERA WITH RF DOWNLINK**
- **ON-BOARD OPTIONAL MAGNATOMETER WITH RF DOWNLINK**
- **ON-BOARD COMPUTER CONTROL SYSTEM**
- **REDUNDANT RF UPLINK CONTROL SIGNALS**
- **SIMPLE TO LEARN AND OPERATE JOYSTICK GROUND CONTROL SYSTEM**
- **USES REGULAR GASOLINE (2 HOUR FLYING TIME)**
- **ON-BOARD INERTIAL STABILIZATION SYSTEM**

FIGURE 5

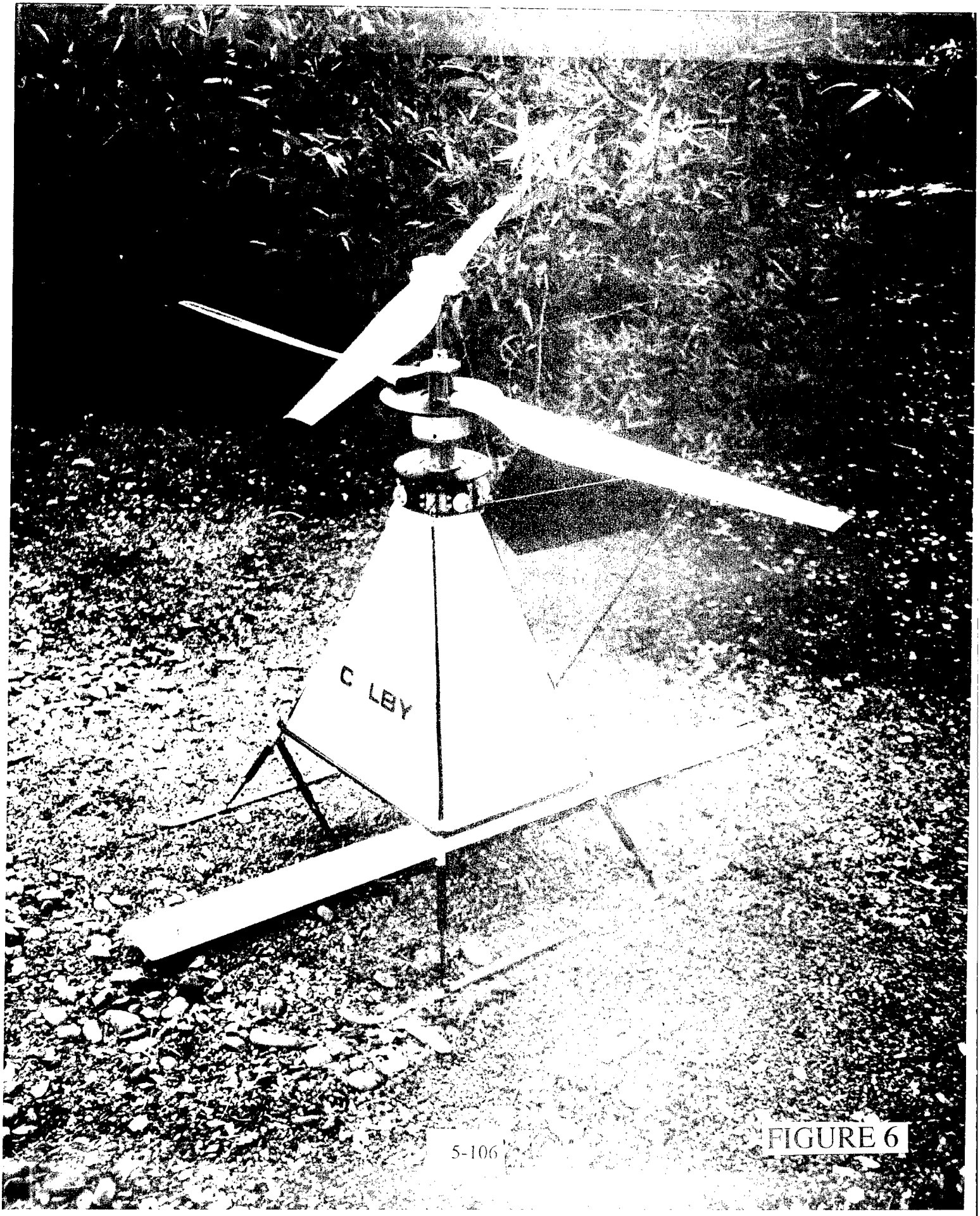
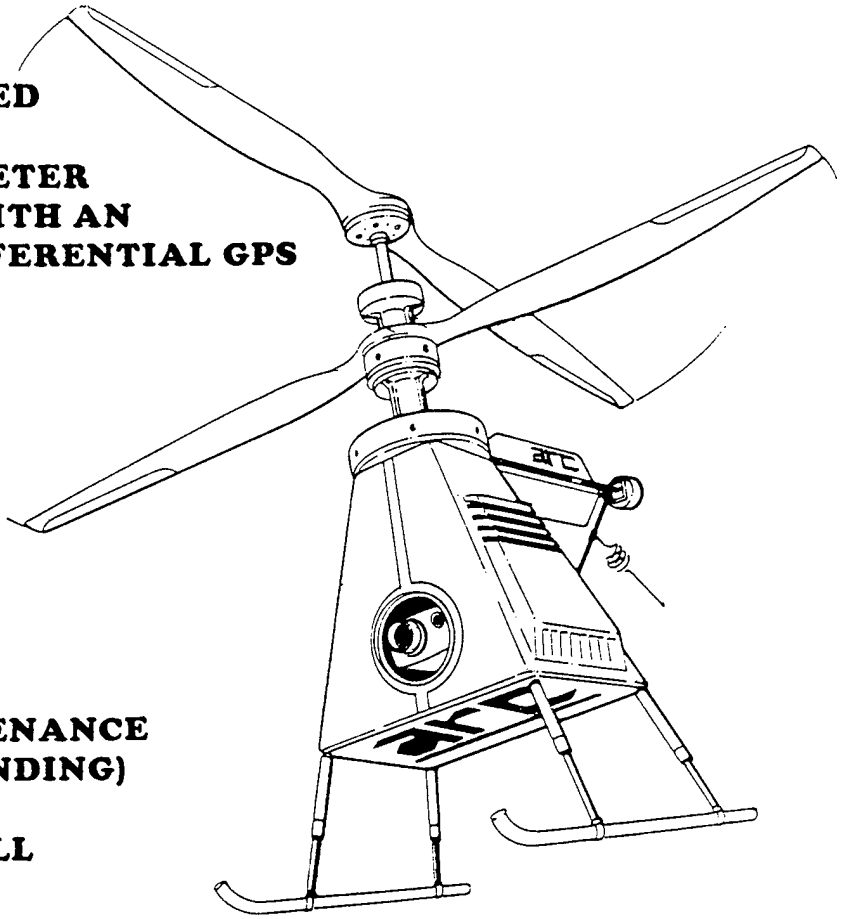


FIGURE 6

NEW!

LOW COST AUTONOMOUS MINE-FIELD SEARCH AND DESTROY VEHICLE



- COMPUTER AND GPS CONTROLLED
- ON- BOARD CESIUM MAGNETOMETER CAN LOCATE MINES AND UXO WITH AN ACCURACY OF 10 CM USING DIFFERENTIAL GPS
- DATA AND VIDEO DOWNLINKS
- PATENT-PENDING IN-PLACE MINE DETONATION METHOD
- 30 LB PAYLOAD
- 2-3 HOUR FLIGHT TIME USING AUTOMOBILE GRADE GASOLINE
- SIMPLE, LOW-COST, LOW-MAINTENANCE AIRFRAME DESIGN (PATENT-PENDING)
- CAN BE OPERATED BY LOW-SKILL PERSONNEL
- UPS AND FED-EX SHIPPABLE

PLEASE CONTACT:
CHARLES COLBY

WE ARE SEEKING:

- STRATEGIC RELATIONSHIP PARTNERS
- FUNDING TO FINISH R & D
- CUSTOMERS AND END USERS

arc
Aero Nautical Robotics Corp.

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FIGURE 7

Fully Autonomous Land Vehicle For Mine Countermeasures

Raymond C. Daigh, *RAHCO International*
Phil Rice, Lockheed Idaho Technologies Company

BIOGRAPHY

Mr. Raymond C. Daigh is currently the Chief Electrical Engineer for RAHCO International. He brings over twenty years of experience in controls engineering to his position. His experience is derived from such diverse industries as nuclear power, integrated circuit manufacturing, pulp and paper production, and silicon wafer inspection and handling robotics.

Mr. Daigh graduated with high honors from Idaho State University and received the CEI Scholarship his final year of school. Prior to attending Idaho State University, Mr. Daigh dedicated eight years of service to the United States Navy aboard fast attack submarines, during which he was EOOW/EWS (ETN 1-SS/DV). He currently resides in northern Idaho with his wife Karen and three children; Geoffrey, Alex, and Madison. Mr. Daigh dedicates his success to his family.

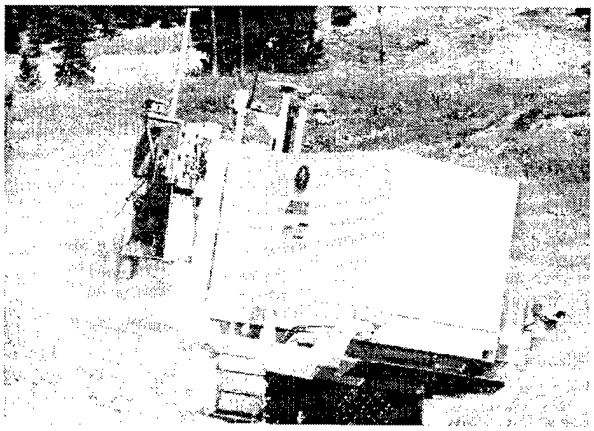
ABSTRACT

RAHCO International, in partnership with the Department of Energy, has developed a 40 ton, prototypical, track mounted, unmanned ground vehicle for hazardous environmental remediation. This unmanned vehicle is capable of navigating preprogrammed courses accurately within 12 inches at a speed of 3 feet per second to transport transuranic waste. This paper will detail our current developments in: dead reckoning, differential global positioning, ultrasonic obstacle avoidance, three dimensional video telemetry, and health monitoring systems. It will also describe the results of a technology demonstration conducted in August 1995 at Idaho National Engineering Laboratories (INEL).

RAHCO will also describe future applications including nuclear facilities, ordnance disposal sites, and ordnance test sites, and discuss system enhancements such as latency reduction, on board autonomy, mission planning, vehicle control command generation, and man/machine interface systems. In the future, the vehicle will be able to accurately operate at a higher speed. To achieve this, control and Global Positioning System (GPS) latencies and telemetry lagtimes will be reduced and implemented in a highly reliable architecture. We will operate the system on multi tasking and multi processing platforms in an applications protected environment utilizing parallel processing architecture for real time control.

PROJECT HISTORY

During 1994, a Telerobotic Transfer Vehicle (TTV) demonstration was performed for the Department of Energy's (DOE) Buried Waste Integrated Demonstration (BWID) program. RAHCO International designed and manufactured the vehicle and subcontracted SPAR Aerospace and RSI Research to implement the vehicle guidance and control system. The TTV was a remote controlled, robotic vehicle capable of receiving and transporting buried waste across a variety of ground conditions. This vehicle was designed to transport and contain transuranic waste while generating a minimal amount of dust during all phases of operation. The vehicle's remote control system consisted of microprocessors running a real time operating system on a



Self Guided Transport Vehicle

modular microcontroller. RS485 bus communications linked the microcontrollers providing interoperability and a parallel processing platform. Three controllers were located on board the TTV and one located at the control station. Video visioning, ultra sonic ranging, and safety shutdown systems were also incorporated into the TTV design.

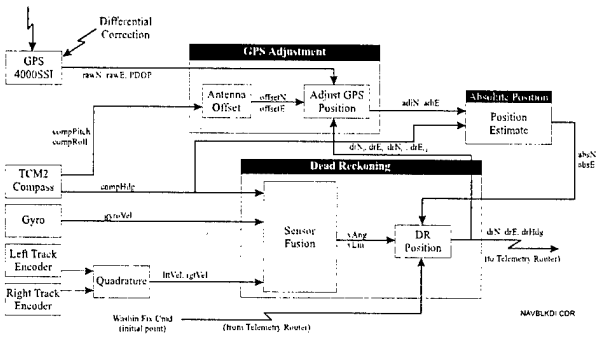
Following the 1994 demonstration, the DOE commissioned further vehicle and control system enhancements including self guidance features and new vehicle designs to improve overall performance. This led to a complete vehicle redesign and rebuild. A Global Positioning System (GPS) based dead reckoning system, graphical user interface, and control algorithms were also developed and installed. The SGTV retained the TTV on board control format but expanded from three to five on board microcontrollers and from one to two operator station controllers. In addition, a primary pentium based man machine interface was integrated. All of these system modifications transformed the TTV into the Self Guided Transport Vehicle (SGTV).

MECHANICAL ENHANCEMENTS

Changing the TTV configuration to fit the SGTV required a complete mechanical redesign. The track hydraulics were converted to closed loop servo pump control to reduce hydraulic latency. A new 100 Hp diesel engine was installed to improve performance. Also, the integrated transport modules, (waste containers), were redesigned and implemented in disposable materials. The waste transport container and bed plate were re-configured for end loading. A systems health monitor was also installed.

SELF GUIDED IMPLEMENTATION

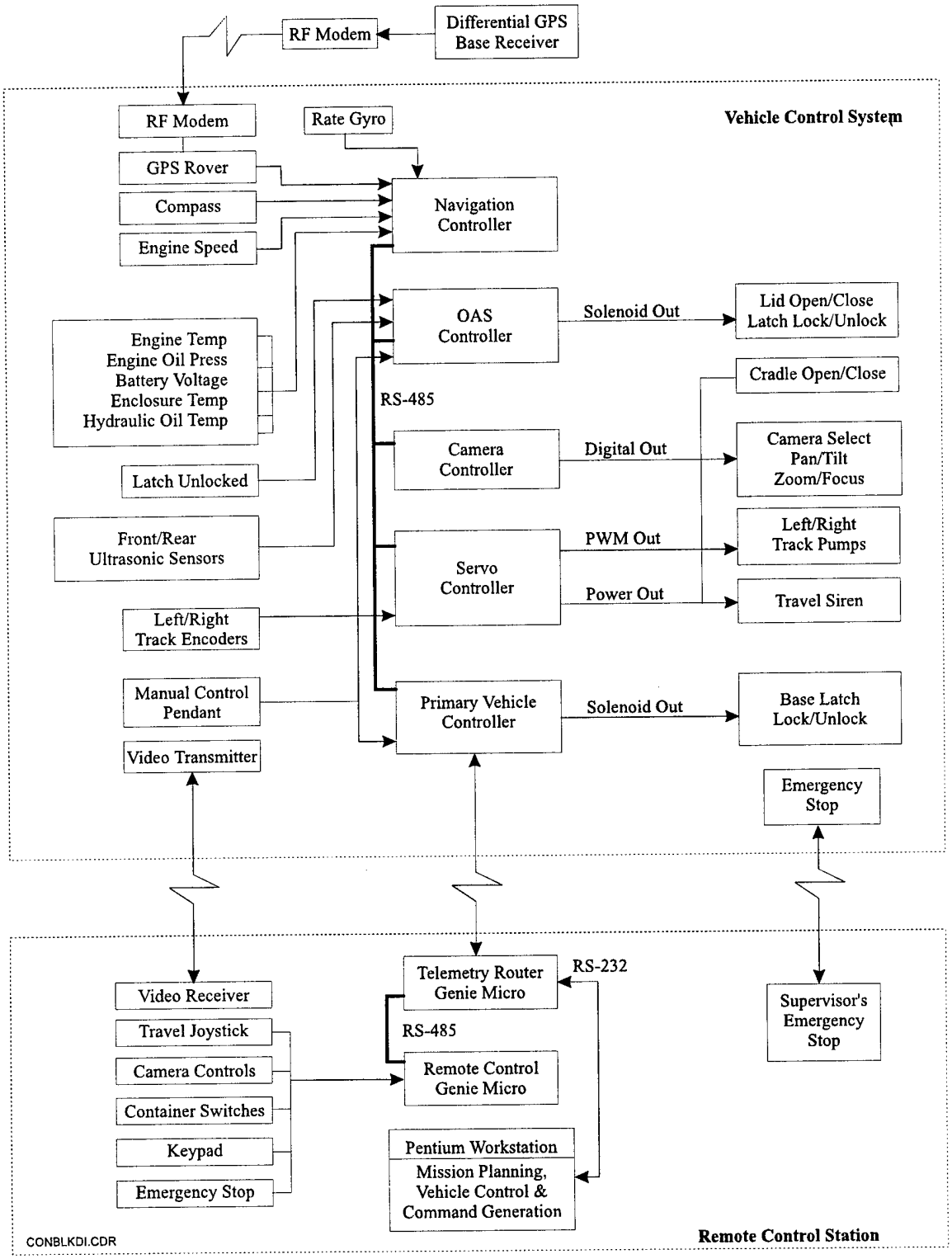
The SGTV Navigation block diagram shows the system sequence that provided real time, dead reckoning, position information. This information was generated through using a rate gyro,



Navigation Block Diagram

electronic compass, and two track encoder sensors. Angular rate information was provided by the rate gyro to approximately .002 degrees per second with .05% linearity. The electronic compass provided heading information to 1.0 degree accuracy and pitch and roll information to 0.2 degree accuracy. Track encoders were selected to provide maximum resolution without overflow in the microcontroller. The resulting resolution was 3/8 inch of travel with theoretical velocity accuracy of .16 feet per second at maximum speed.

Track encoder signals and compass headings were used to mathematically generate angular velocity signals. These were fused with the rate gyro signal (gyroVel) using a weighted "least squares" estimator favoring the encoder signal. Overall velocity signal weighting was determined empirically during testing to optimize angular velocity (vAng) signal reliability.

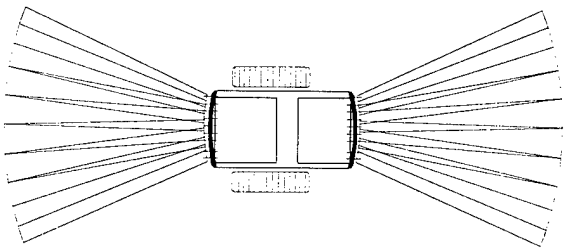


System Controls Block Diagram

Compass heading signals were fused, each computational cycle (20 Hz), with derived heading information from the track encoders and the rate gyro which produced a combined measurement (drHdg) better than its parts. The final sensor fusion was averaging the two track encoder's linear velocity (vAng). This system of redundant signals provided a high level of flexibility in sensor usage and greater overall dead reckoning system reliability. Pitch and roll data derived from the compass was used to correct DGPS position (adjN, adjE) for operation on uneven terrain. Reported position and heading (drN, drE, drHdg) was the result of correcting the dead reckoned position divergence with the adjusted DGPS position in a supervisory control loop. This correction took place at 2 Hz while the dead reckoning system calculated positions at 20 Hz. Important safeguards incorporated into the overall design included the compass' ability to detect and report magnetic anomalies that could compromise the heading signal. Several differential GPS (DGPS) system error detection flags were also included in the dead reckoning supervisory controls.

Several GPS receiver features were utilized to transform the WGS-84 coordinates the receiver normally reported to a local coordinate grid system. The resulting grid coordinate system was also transferred to the mission planning map for route planning and tracking at the operator's station. This on board receiver data reduction decreased telemetry requirements and provided small integer coordinates for the microcontroller arithmetic calculations.

Collision Prevention System



Ultrasonic Ring Array

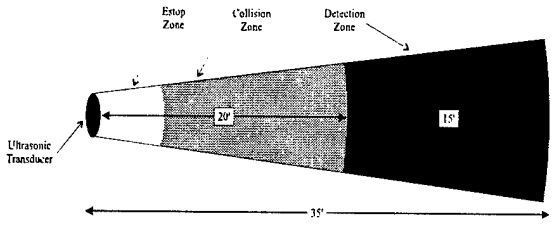
In addition to a primary navigation system, it was necessary to develop a collision avoidance system that complemented the basic navigation functions. The collision avoidance system consisted of an array of broad beam ultrasonic sensors mounted on each end of the vehicle. Each array of coordinated pulse sensors consisted of nine transmitter receivers that operated with overlapping convergence zones in a ring configuration. This resulted in 3 feet of side coverage at a range of 17 feet, with the only discontinuance in beam coverage occurring between the vehicle and 5 feet of range. These spaces uncovered by the beam were very narrow triangular areas located inside the emergency stop range. For the purpose of velocity control, there were two sonic zones.

Detection Zone -

An outer area where obstacles are detected and the operator is alerted but no automatic action is taken.

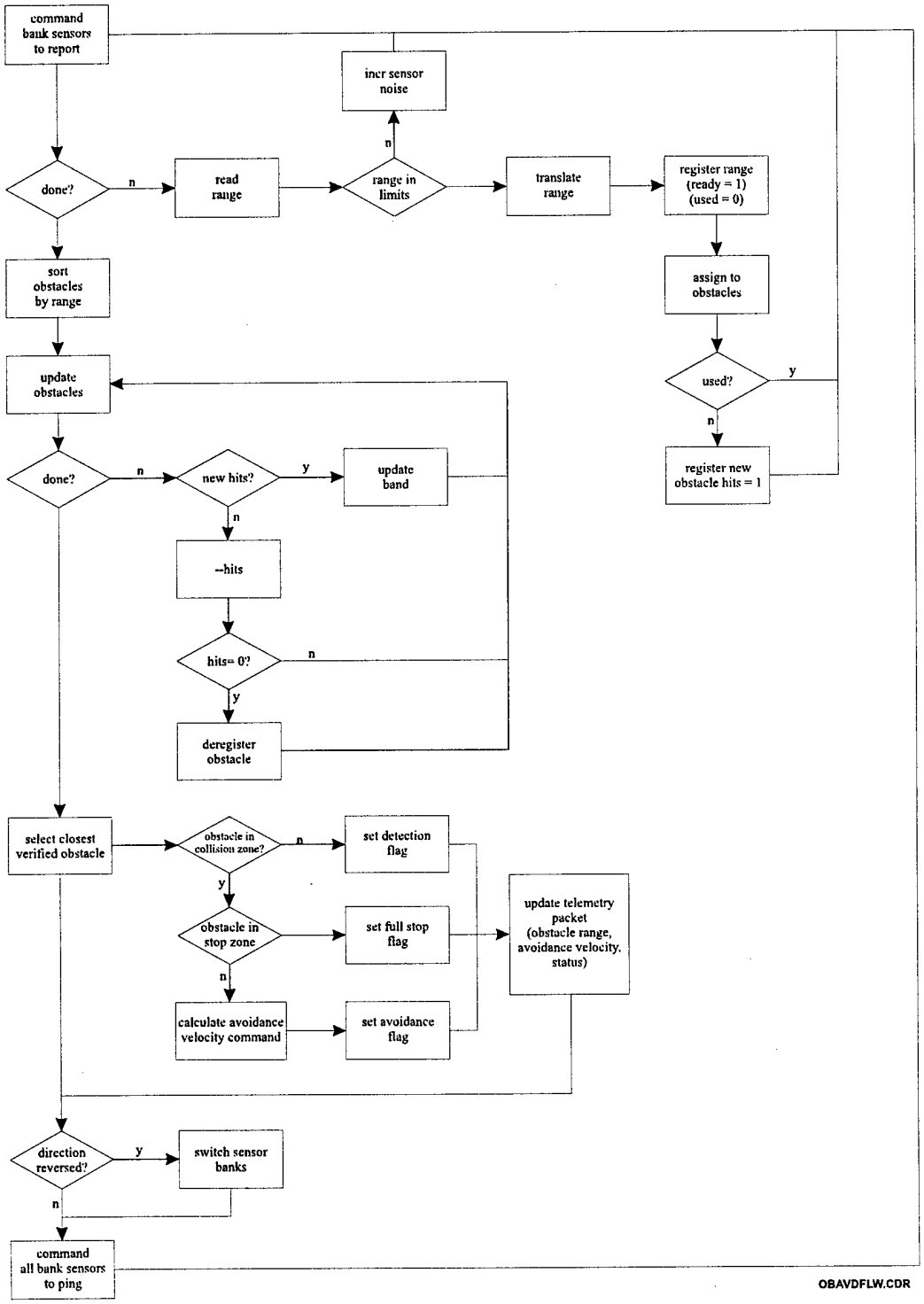
Collision Zone -

The inner area where vehicle velocity is automatically reduced to ensure the vehicle is stopped within a safe distance from the obstacle. The operator station is also alarmed. When two consecutive echoes of the same sensor occurred within a mathematically expected range, a target obstacle was confirmed. (Refer to the upper loop of the Obstacle Avoidance Flow diagram on the following page.) This confirmation technique doubled the ultrasonic response time resulting in a 2.5 Hz lag or 2 feet of travel



Balanced Collision/Detection Zone

Obstacle Avoidance Flow



between the first echo and confirmation. In order to provide controlled vehicle deceleration, a collision to detection zone ratio of 20:15 was chosen for proper algorithm balance. Incorporation of hydraulic latency and braking time resulted a minimum stopping distance of 6 feet at 5 feet per second velocity. Therefore, an active emergency stop zone was included for any single echo inside of six feet. An allowance was made to identify and register nine separate obstacles and calculate avoidance velocity reductions for the closest one, as shown in the central loop of the Obstacle Avoidance Flow Diagram.. When an obstacle disappeared from the vehicle's sensing zone, based on a lack of echoes within the tolerance band of a registered obstacle, the system would reset and then restore normal velocity control. For close approach and vehicle docking, the emergency stop zone stopping distance was coordinated with the vehicle's actual speed to gradually approach but never reach, a zero distance. This permitted a very slow speed docking without eliminating the emergency stop zone. The bottom loop of the Obstacle Avoidance Flow diagram shows functional implementation of the supervisory velocity controls. Another important system feature was coordinating the sensor bank selection with travel direction and implementing bank switching on the basis of net linear velocity as derived from the track encoders.

AUXILIARY SENSOR SYSTEMS

Vehicle auxiliary sensor systems included all normal engine and hydraulic alarms and waste transport container lid and latch system robotics control. These systems were integrated into the overall on-board control architecture and distributed among the on board micro controllers. This resulted in auxiliary subsystem reliability and equal processor loading between micro controllers.

SYSTEM INTEGRATION

All physical and digital interfaces for the entire system are shown in the System Controls Block diagram. Overall integration was facilitated through use of the RS485 busses between the microcontrollers on board the vehicle and the remote control station. The real time operating system allowed a high degree of customizing and streamlining communications within the data transfer between modules. Telemetry data transfer between the vehicle and the remote operator's station was a tightly defined optimized data packet utilizing Cyclic Redundancy Check as the main control communications. Additional telemetry systems included video communications for the vehicle vision system, differential GPS corrections, supervisors dead man switch, and emergency stop. Independent communications' channels allowed isolation of critical information from nonessential data and improved vehicle reliability. The remote station's video vision system camera controls, telerobotic remote control, and primary operator interface communicated by close coupled serial links. The control center was configured as a three part system consisting of the modified TTV remote controller, mission planning computer, and vehicle control command generator (VCCG). The mission planning and VCCG algorithms were written in visual basic and tested in interpreted code for monitoring and modification ease. This approach was satisfactory for the relatively low speed demonstration requirements of real time kinematic control.

Mission Planning GUI

The mission planning interface was designed to provide ease of use and point and click operability. Fundamental setup was based on a scaled operating area map with known obstacles-buildings, trees, and other fixed equipment-overlaid by no go zones with adjustable exclusion borders. The pre-planned vehicle route was drawn on this scaled map. A predefined waypoint was established at each route location where the vehicle heading changed. Each waypoint had its own set of parameters within the transition area.

Waypoint Navigation

The waypoint method of vehicle control was chosen to provide segmented mission control and definitive means by which navigation precision was measured and logged in real time. The VCCG logged vehicle data during operation, which was used as the basis for statistical system performance analysis. There were five different types of waypoints, each with similar characteristics. Through the linear segments, Global operational parameters were in effect for linear and angular velocity. At each waypoint the Washin and Washout Circles permitted customizing the global control parameters for each waypoint type.

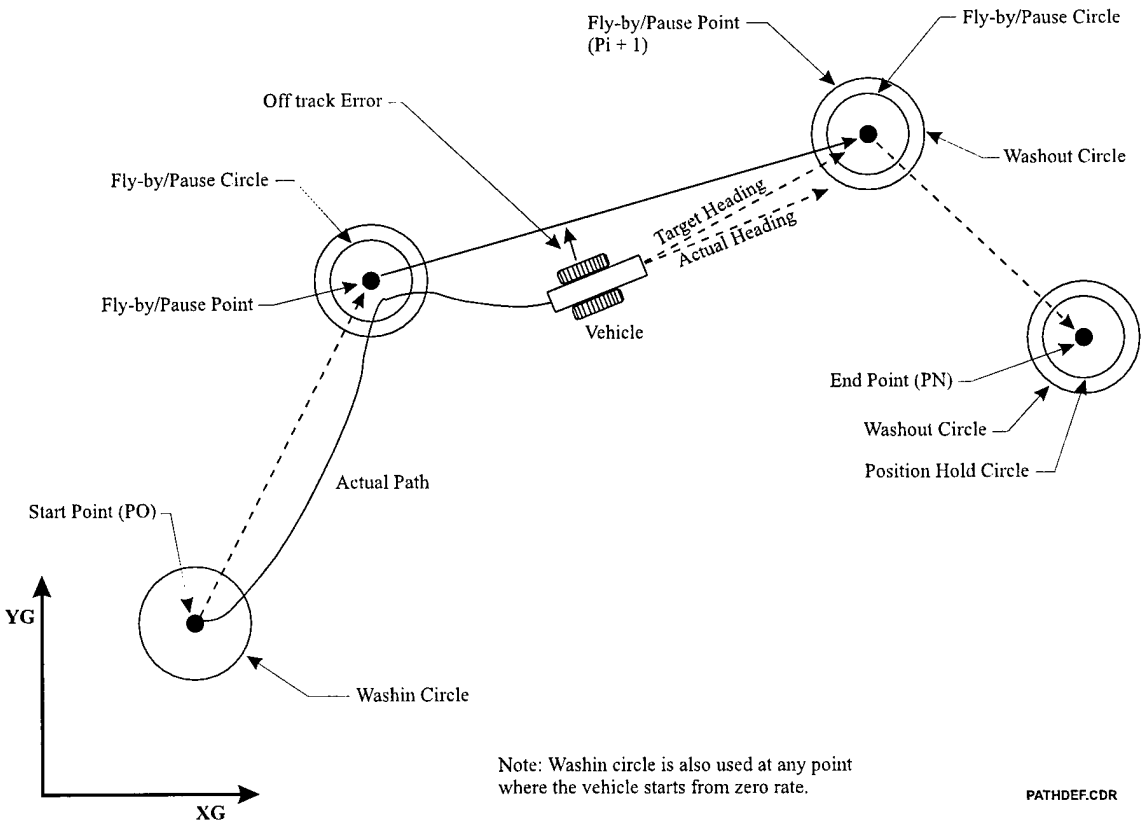
Start Point -
The starting point for the mission. The vehicle will proceed to this point in a direct line from its current location.

Fly by Point -
A point on the course where a pivot turn is performed.

Smooth Flyby Point -
A point on the course where a radius turn is performed.

Pause Point -
A stopping point along the path where the path tracking may be resumed.

End Point -
A docking location at the end the path.



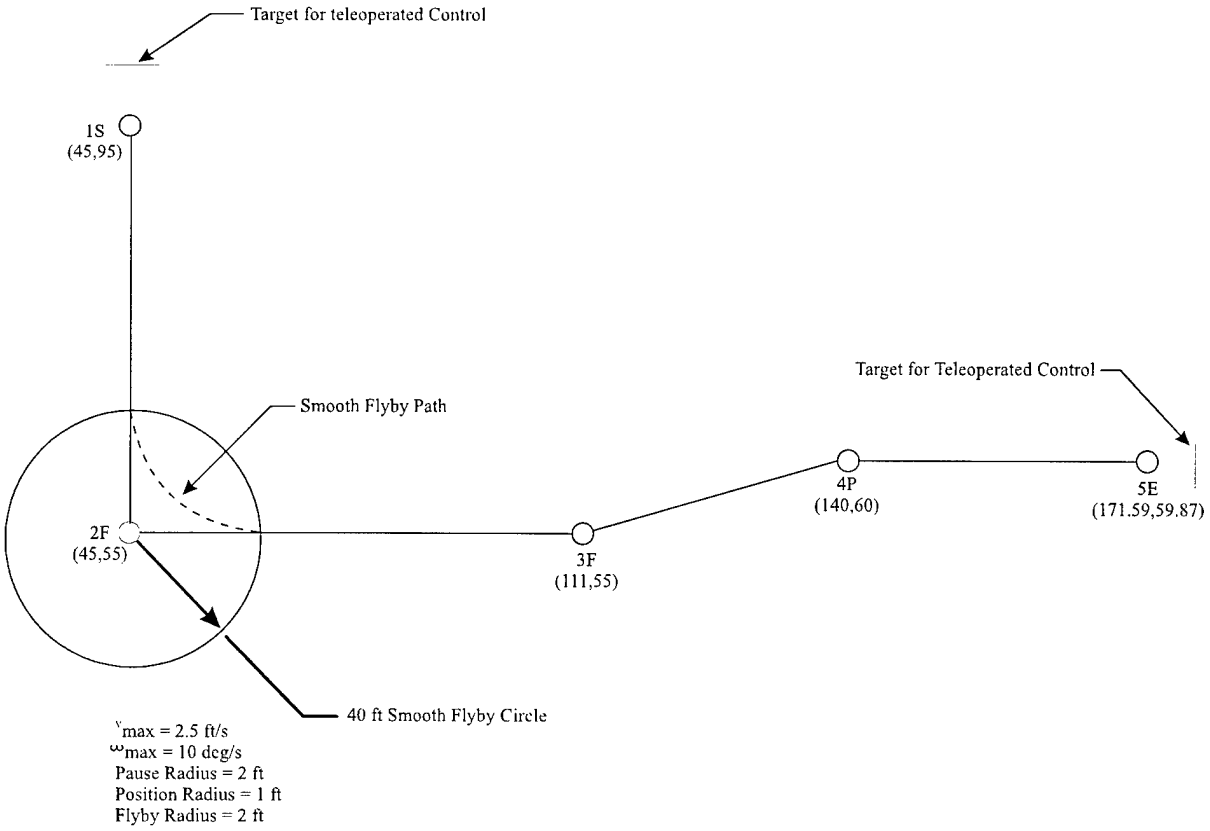
Path Definition

During normal operation the vehicle operated continuously on the basis of off track error correction to the next waypoint. The vehicle heading was therefore corrected continuously to ensure arrival at the next waypoint. Minor deviations in track and heading were expected at the Washin Circle.

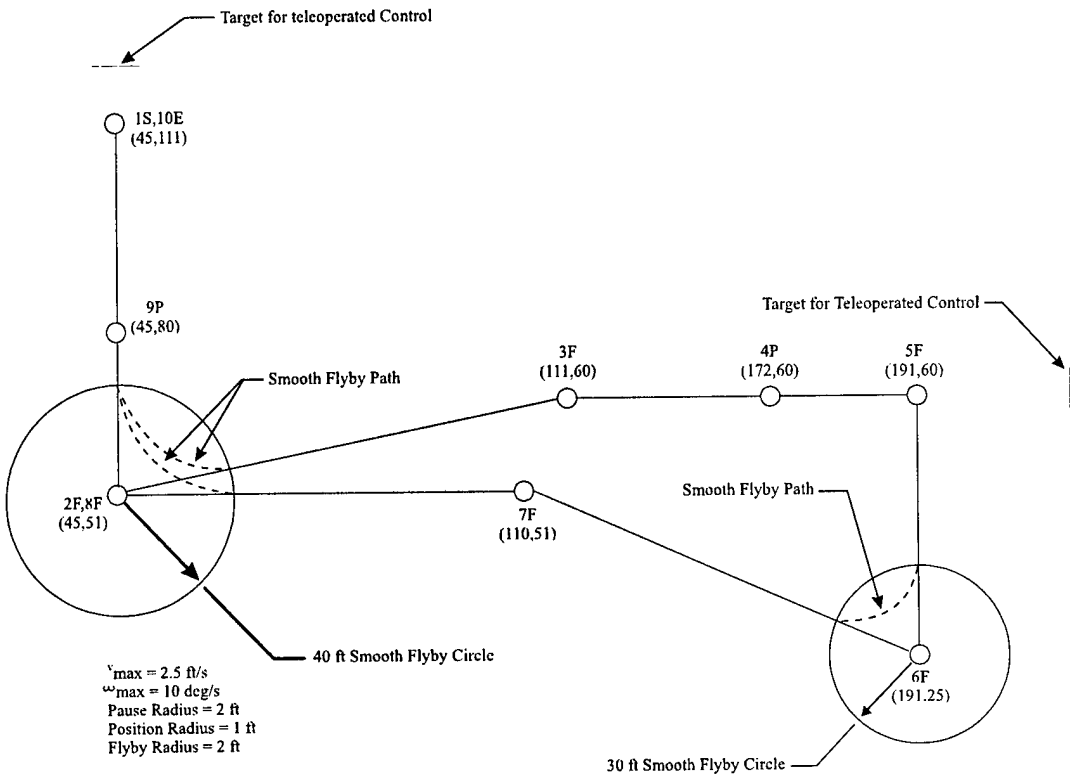
Vehicle Control Command Generator GUI

This interface was the primary monitoring interface for vehicle operation. It included all of the mapping and path planning generated in the mission planning MMI and all of the vehicle operating system monitors. The display also traced the vehicle path against the planned path in real time and allowed operator intervention when necessary due to receiving any one of several alarms or abnormal condition reports.

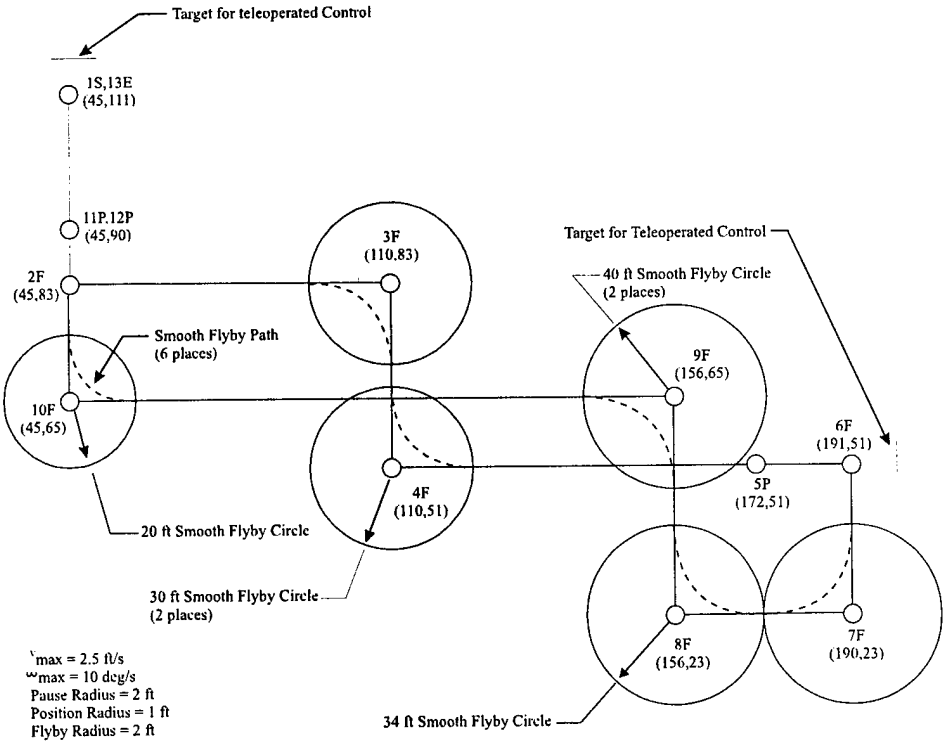
The control algorithms running under the VCCG performed all travel control and systems safety interlocking functions. The autonomous control system and TTV joystick controller outputs were identical in design. In fact, the on board systems did not differentiate between the two control methods. The control station's telemetry router determined which control signal source was transmitted to the vehicle, either TTV joystick or VCCG. From this MMI it was possible to define all mission tuning parameters. These included velocity, acceleration, and deceleration parameters for both linear and angular motion, minimum and maximum radius' for flyby waypoints, and tuning parameters for control loops.



Path 1


Target for teleoperated Control
1S,10E
(45,111)
9P
(45,80)
Target for Teleoperated Control
3F
(111,60)
4P
(172,60)
5F
(191,60)
Smooth Flyby Path
2F,8F
(45,51)
7F
(110,51)
Smooth Flyby Path
40 ft Smooth Flyby Circle
6F
(191.25)
30 ft Smooth Flyby Circle
ᵛmax = 2.5 ft/s
ᵚmax = 10 deg/s
Pause Radius = 2 ft
Position Radius = 1 ft
Flyby Radius = 2 ft

Path 2


Target for teleoperated Control
1S,13E
(45,111)
11P,12P
(45,90)
3F
(110.83)
Target for Teleoperated Control
40 ft Smooth Flyby Circle
(2 places)
2F
(45,83)
Smooth Flyby Path
(6 places)
9F
(156,65)
10F
(45,65)
6F
(191,51)
4F
(110,51)
5P
(172,51)
20 ft Smooth Flyby Circle
30 ft Smooth Flyby Circle
(2 places)
8F
(156,23)
7F
(190,23)
34 ft Smooth Flyby Circle
ᵛmax = 2.5 ft/s
ᵚmax = 10 deg/s
Pause Radius = 2 ft
Position Radius = 1 ft
Flyby Radius = 2 ft

Path 3

DEMONSTRATION RESULTS

Three mission plans varying in complexity and layout were used for navigational testing. [1]The first course was a relatively simple "L" configuration with a dog leg in the longer side, as shown in path 1. The total length of this route was 316 feet including the return path which was the reverse of this path. The mean navigation time for 10 transits was 134.6 seconds. The mean off-track error was .602 feet with a bias of -.373 feet, a standard deviation of .842 feet and a mean absolute deviation of .580 feet.

The second course, path 2, was an offset closed loop triangle with a docking station approximately 90 degrees from a vertex. For ten runs the mean transit time for this path was 354 seconds for the 408 foot circuit. Calculated mean off-track error was .634 feet with a bias of -.233 feet, standard deviation of .972 feet and a mean absolute deviation of .653 feet.

As in path number two the third path started and ended in a simulated docking station. In this path the closed loop circuit consisted of 5 "L" shaped segments overlapped between the forward and reverse paths. This was the most rigorous path tested for the vehicle's intended purpose of retrieving containers of low level radioactive waste. The results were again encouraging since the system performed within the 1 foot tracking goal on the desired course.
During the entire course length of 428 feet, the mean travel time was 421 seconds with a mean off-track error of .709 feet and a bias of -.118 feet. The standard deviation was .934 feet and the mean absolute deviation was .711 feet for ten runs.

DEMONSTRATION CONCLUSION

The vehicle performed within the required 1 foot tolerance for ground tracking and successfully performed docking maneuvers.[2] In all cases the system, under autonomous control outperformed operators in telerobotic control. With the inclusion of the redundant safety systems the vehicle never presented an unsafe condition during any of the three month checkout or testing periods.

VEHICLE ENHANCEMENTS

A primary refinement transferring all VCCG functions on-board to eliminate the real time telemetry loop used for control in the current configuration. This will, in theory, reduce latencies and enable speeds above 20 mph. One method would be to translate and transfer the C code for the VCCG to an additional genie micro controller on board the vehicle. Another would be to abandon the micro controller network and adopt the on board functions in a Eurocard style Pentium Pro multi processor platform with a real time applications protected operating system. Any of these options need to be implemented in a fully industrialized and hardened package.

Another enhancement would be the evaluation of alternate sensor packages and navigation systems. A very promising technology would replace the entire dead reckoning system with a Trimble Tans Vector GPS attitude determination system coupled with a 7400 MSI DGP system. Present research has shown these systems to be effective indoors under lightweight ceilings.

The electronics package on board the vehicle was subjected to fairly high shock and vibration forces which induced RS 485 network failures and caused some physical damage to the electronics. It is worthy to note that during operations these failures were for the most part recoverable on the fly. A production version would need to compensate by potting all electronics and adapt a better shock mounting system. Overall the reliability of the system could be improved through the incorporation of commonly available hardware and connector improvements.

FUTURE APPLICATIONS

In addition to transporting hazardous waste, the SGTV and its guidance and control technology has a variety of future applications. This vehicle could be used to transport toxic and hazardous chemicals where minimizing the danger to the equipment operator is desired. Use of an SGTV

equipped with robotic manipulators to retrieve and transport plutonium or other radioactive materials is currently possible. Additionally, the basic technology exists today to provide a completely autonomous vehicle capable of performing mine countermeasure activities on land, in shallow water, and in surfzones without risking the lives of U.S. military personnel.

SUMMARY

Autonomous vehicle technology advancements are expected to be a continued priority well into the 21st century. This is primarily due to the increased need and interest in physically safe methods of remediating environmentally hazardous areas. Current vehicle technology allows accurate, short range, mission deployments. The SGTV provides a perfect platform for a multitude of application modifications yet maintains flexibility for future enhancements. During the technology demonstration the SGTV proved it could travel pre-planned courses within 9 inches at speeds up to 5 miles per hour. Obstacle avoidance and supervisor safety systems complete the GPS strapdown dead reckoning navigation package ensuring safe, reliable operation. The technology demonstration was deemed a success considering the low research and development costs and short nine month schedule from conception to completion.

ACKNOWLEDGMENTS

It is the pleasure of the authors to acknowledge all of the countless hours of devotion and the tireless effort of Dave Lockhorst and all the employees of RSI Research and to extend our gratitude to Patrick Fung and all of those at SPAR Aerospace, who are involved in this project, for their persistence and insight.

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ADVANCED TECHNOLOGY: IT'S AVAILABLE AT JPL

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The Jet Propulsion Laboratory (JPL) of the California Institute of Technology is a Federally Funded Research and Development Center (FFRDC)located in the foothills above Pasadena. JPL operates under a contract between Caltech and the National Aeronautics and Space Administration (NASA), wherebye Caltech staffs and operates the Laboratory in performing its NASA designated role as the lead center for the unmanned exploration of the solar system - and beyond. Current staffing is approximately 5500 - all Caltech employees - with an annual budget over one billion dollars.

Explicit in the Caltech/NASA contract is a provision authorizing that up to a quarter of JPL's work-years' effort may be applied to non-NASA oriented activities. This reflects a joint NASA/Caltech philosophy that the techniques and technologies developed to support the unmanned planetary exploration program - all at public expense-may have applications in other areas, and a concerted effort should be made to investigate such opportunities. These non-NASA activities are the province of the JPL Technology and Applications Programs Directorate, and include working relationships with industry, academia, and other government agencies. Within this Directorate, the JPL Undersea Technology Program endeavors to apply and transfer these capabilities to the area of underwater research and operations.

The operational requirements of unmanned space exploration bear striking similarities to those imposed by operations in and on the oceans. We are faced with the development and operation of sophisticated, extremely reliable vehicles, operating unattended for periods measured in years, in remote locations, in unknown and often hazardous environments, and with rigid constraints on weight, size, power and - increasingly - costs. Within these constraints, it is desired to maximize the sensor complement and information return, often over bandwidth limited channels. These same requirements and constraints must sound very familiar to those operating in the oceans, particularly with ROV's and AUV's.

Because of the extreme distances involved in planetary exploration, and the consequent long delays in communication times, planetary spacecraft of necessity must rely heavily on intelligent and autonomous onboard systems. One advantage we may have over marine operators is that we don't worry about losing our vehicle - once it's launched, we KNOW we're not going to get it back!

This inability to retrieve our vehicles, however, does place extreme emphasis on quality control, and component and system functional reliability. Successful missions have depended on the development of techniques and technologies to assure that things work - unattended - for very long periods of time. The two Voyager spacecraft, launched in 1977, have explored all the planets in the outer solar system - except Pluto - and are now exiting the solar system and trying to detect the galactic interface. They are still operational, and we remain in communication with them - at distances of five to six billion miles - via their on-board 25 watt transmitters!

Of significant interest in space - and ocean - operations is the trend toward miniaturization. Currently at JPL, the Cassini spacecraft is being assembled; it will be launched about a year from now and will proceed to Saturn on a 7 year VVEJGA (Venus,Venus,Earth,Jupiter Gravity Assist) trajectory,where it will go into ever changing

orbits for a design period of four years, exploring the planet and its satellite system and discharging a probe into the atmosphere of Titan. The spacecraft is about three stories high, weighs about 5 tons, and carries the most extensive and sophisticated set of instruments ever flown. It is also a billion dollar project. Missions on that scale, and perhaps launched only once in a decade, are no longer affordable or desirable - nor are they necessary. The emphasis is on smaller, lighter, lower powered, and cheaper vehicles.

JPL's Space Microelectronics Program is developing the technology to satisfy all of those criteria. Fig. 1 shows a comparison or progression (downsizing) from Cassini to a possible micro-spacecraft of the future, utilizing a variety of the JPL developed micro-sensors and associated technology. This effort has produced a number of miniature sensor packages, including ,for example: accelerometers, seismometers, radiometers ,hygrometers. A hydrophone developed for the Navy is encapsulated in a 1 inch sphere. (Fig 2). In addition to small size, these devices exhibit extreme sensitivity, ruggedness, and very low power consumption.

Of particular interest may be a Reversed Electron Attachment Detector (READ). It is a man-portable device capable of unambiguous detection of unique chemical signatures associated with mines. READ has demonstrated the ability to detect 2,4-DNT; 2,4,6-TNT; PETN; and RDX in parts per trillion concentrations, as well as nerve and blister agents and non-conventional explosives such as perchloro and peroxy compunds.

Utilizing complementary metal-oxide semi-conductor (CMOS) technology, JPL has developed a new imaging sensor - virtually a camera on a chip - promising smaller and cheaper imaging systems but comparable in performance to the current state of the art (Fig. 3). This active pixel sensor technique represents a considerable leap beyond the widely used charged coupled device (CCD) technology. Use of the CMOS sensors presents the opportunity for reducing imaging costs, power and size, and improving reliability.

The thrust toward miniaturization places a concomitant need for improved power sources. The Laboratory has an extensive effort devoted to advanced power sources featuring small size, long life and increased specific energy. In the range up to 100kW and specific energies to over 200 watt-hours/kg, Fig 4 shows a number of cell types under consideration, development and test. An "AA" $LiTiS_2$ cell has been successfully cycled 1,000 times to 50% discharge at ambient temperature. Also under development (Fig 5) is a direct methanol, liquid feed fuel cell where a 3% methanol/water mixture is the fuel and air is the oxidant. Advantages include simplicity, start up at room temperature, operation at 70° to 90°C, and no resulting pollutants, the only outputs being potable water and CO_2. The system is modular, with a 4 x 6 inch cell providing 50 amperes continuously at 0.4 volt,at 90°C with air. Plan is to demonstrate a 1kW fuel cell stack next year.

In addition to the above, other JPL technologies which merit investigation for marine applications, include - but are not necessarily limited to: teleoperators/robotics; roving vehicles; communications; data collection,processing compression; digital imaging and visualization; guidance,control, navigation; and certainly quality control and systems integration.

Teleoperator/robotic activities range in size and function from a large, seven-degree of freedom arm being developed for NASA use as an autonomous surface inspection device for the Space Station, to a micro-surgery device for medical applications, e.g., inside the eyeball surgery. The NASA arm incorporates an eddy current sensor for detection of minute pits or cracks, as well as a proximity sensor to avoid actual contact

with the surface. The micro-surgery device is being developed in conjunction with an eye surgeon, and has an accuracy/repeatability of ten angstroms. The device will also eliminate any tremors resident in the surgeons hands, even his pulse beat. Also in the laboratory is a modular, eleven degree of freedom arm, about 2 inches in diameter, which permits access into intricate, complex passages.

An autonomous roving vehicle, "Sojourner" (Fig 6), will be mounted inside the "Pathfinder" spacecraft, which will be launched this coming December and will land on the surface of Mars on July 4, 1997. After landing, "Pathfinder" will unfold and deploy the rover onto the surface of Mars. It will be directed to explore certain targets or areas, navigating on its own, and performing engineering and scientific experiments. "Sojourner" will transmit its information to the lander for re-transmission back to earth. The rover's prime power, 16 watts, is provided by a 0.2 square meter solar panel, backed up and augmented by lithium sodium di-oxide "D" cells.

New autonomous control and data processing methodologies are being developed which can be applied to underwater target detection, where transmitted pulse sequences form a non-gaussian process in the presence of ambient/environmental noise. Using these statisitical techniques with inherently efficient algorithms for emerging parallel computational architectures (e.g. systolic arrays, neural networks) will result in effective "near optimal' algorithms for high performance, real-time underwater signal and target detection, identification and tracking. Additionally, the autonomous control methods will enable unmanned underwater manuevering with complete failure detection, identification and recovery capability.

Because of the crippled 16 foot diameter high-gain antenna on the Galileo Jupiter orbiting spacecraft, communications have had to rely on the much smaller low-gain antenna, with a consequent decrease in transmission rates from an expected 135 kbs to less than 2 kbs. To compensate, JPL communications researchers have devised methods to extract the maximum amount of information from this abridged data stream. The technique is described as a "feature driven data compression technique for bandwidth critical applications". Since underwater transmissions are typically bandwidth critical, this approach may offer increased information transmission over a given bandwidth.

Underway at JPL is a 3-year technology demonstration program,"MUDSS" (Mobile Underwater Debris Survey System) funded by the Strategic Environmental Research and Development Program (SERDP) in the Cleanup thrust area. Its purpose is to demonstrate technologies necessary to successfully survey underwater "formerly used defense sites"(FUDS) for ordnance and explosive waste (OEW). The program is a joint Department of the Navy and NASA effort being executed by the Naval Sea Systems Command's Naval Surface Warfare Center (NSWC), Dahlgren Division, and the Jet Propulsion Laboratory. The first year of the effort was completed in 1995, to (1) demonstrate that a prototype MUDSS sensor suite shows good promise against inert OEW targets, and (2) provide a multi-sensor data base to be used during Phase II to refine processing algorithms prior to at-sea testing at actual FUDS.

The foregoing provides a brief and necessarily limited introduction to several of the existing technologies which it is felt have application to areas of your interest. Far from satisfying your curiosity, it is hoped that this exposition will serve to arouse your interest and provide motivation to explore further. From our standpoint, the preferred follow-up would be to have you personally visit the Laboratory, which would serve two purposes: (1) it would afford you the opportunity to see hardware and discuss these and other technologies first hand with those directly involved, and (2) it would provide us your

assessment of these technologies and advice as to the direction for future developments. It is a win - win situation!

The Consortium for Oceanographic Research and Education, CORE, undertook an Interagency Partnership Initiative to "reexamine our Nation's posture toward ocean science and technology and establish a new and invigorated partnership concept". The Initiative produced "Oceans 2000: Bridging the Millenia -- Partnerships for Stakeholders in the Oceans". Among its recommendations were: (1) define specific research and education partnership opportunities for academia, industry, and the Federal Government, and (2) develop an integrated partnership management plan to provide effective and cost efficient federally funded ocean science and technology programs.

The 1992 Ocean Studies Board Report, "Oceanography in the Next Decade: Building New Partnerships", in commenting on such partnerships, stated: "In general, partnerships must be extended beyond financial relationships to include the sharing of intellect, experience, data, instrument development, facilities, and labor".

In his keynote address at the JPL Undersea Technology Symposium in May of this year, RADM (Ret) Brad Mooney reviewed preliminary results of the Marine Board Study, "Undersea Vehicles and National Needs". He stated, "An increased role for AUV's is anticipated in all of the areas I've mentioned. AUV's will require the most technological advances for them to be competitive, efficient, and effective, but they promise great payoffs in capabilities as sensors, communications, and control techniques are improved".

The sentiments expressed in the previous three paragraphs are typical of current thinking and reflect an awareness of the stringent budgetary constraints faced by all, and the consequent need to conserve resources and use capabilities wherever they may reside. We at the Jet Propulsion Laboratory invite and encourage your investigation of our capabilities as potential resources for your use.

As Dr. Don Walsh commented in an article in the April issue of "Sea Technology", when referring to the JPL Undersea Technology Program: "A model that right now produces bought-and-paid-for technologies that can be adapted to ocean research and business. TAKE ADVANTAGE! THE PRICE IS RIGHT!"

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Mission Planning for an Autonomous Undersea Vehicle: Design and Results

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Abstract - This paper describes the design of the on-line mission planning system implemented in the Autonomous Minehunting and Mapping Technologies (AMMT) program sponsored by the Defense Advanced Research Projects Agency (DARPA). The AMMT vehicle was designed to survey undersea areas and map the terrain and any potentially mine-like objects. If the mission planner determined it was safe, the vehicle would also image bottom mines. The vehicle is completely autonomous so the planner is responsible for not only generating initial trajectories but modifying the plan to accommodate unforeseen events.

As input, the planner is given a series of high-level activities to perform and their associated utility. The planner must determine the sequence of activities that optimizes the expected utility of the mission while working within operational constraints such as time and fuel constraints. Typical activities include surveying specified regions and imaging targets and getting a GPS navigation fix. The vehicle must obey strict depth and altitude constraints so the execution of each activity requires that both terrain and target obstacles be avoided. The planner does not have any a priori knowledge of the terrain and must rely on data gathered by an ahead-look sonar. As new information about the environment is learned, the planner must re-plan the mission to insure the safety of the vehicle. The planner was successfully demonstrated to work in the AMMT vehicle in both simulation test and at-sea testing.

This paper describes the design of the mission planner, implementation issues and presents results from both the simulation and at-sea tests. Possible enhancements and areas for future research are also presented.

I. Introduction

The Autonomous Minehunting and Mapping Technologies (AMMT) program is a DARPA response to the need for clandestine reconnaissance. AMMT combines precise navigation, adaptive vehicle maneuvering, long-range acoustic communications, underwater imaging, bathymetric mapping, and acoustic tracking and navigation to enable mine and obstacle detection and localization, imaging of underwater targets, near real-time acoustic communications and an over-the-horizon approach to the region of interest.

The AMMT program extended the DARPA UUV's autonomous capability by adding an on-line mission planner. The mission planner is the focus of this paper. The planner provides the flexibility to adapt the mission plan as dictated by the circumstances that arise during the mission.

As input, an operator specifies high level mission objectives that are to be achieved during the mission. The operator also specifies the utility of each objective. The utility is a relative ranking of the objectives. If an objective is twice as important to complete as another objective, then its utility would be twice as much as the other. Along with the objectives, the operator also specifies time and fuel limits for the entire mission. It is the mission planner's responsibility to execute a plan that maximizes the expected utility of the mission using the time and fuel allotted.

Planning is a search through the infinite space of possible decisions to find that sequence of decisions, or plan, that best achieves the given objective. A search algorithm generates possible vehicle trajectories which are then scored using a cost function. The cost function is a weighted combination of the estimated resources (time and fuel) needed to perform each activity in the mission and the utility of each mission objective. The mission planner scales the utility by the probability of completing the objective in the mission. In this manner, a near optimal vehicle trajectory is selected given the specified goals and constraints.

II. Requirements

Perhaps the most important requirement for an autonomous planner is to be able to plan both quickly and effectively. Since the planner typically has no a priori knowledge of the operating environment and the environment is inherently stochastic, plans cannot be generated long before their execution. The planning process must be flexible enough and fast enough to be able to respond to stochastic events without sacrificing the vehicle's safety.

It is not sufficient to merely generate plans quickly; the mission planner is also responsible for generating vehicle trajectories that are safe and achievable. Safe trajectories are trajectories that avoid obstacles, maintain testbox constraints and are robust to sensor dropouts. Obstacles include avoidance stovepipes, sonar targets determined to be tethered

mines or suspended objects and terrain obstacles (water depth constraints). Avoidance stovepipes are locations at which there are known obstacles or otherwise keep-out regions and are specified by the operator. The testbox can be any convex polygon in the horizontal plane and is defined by waypoints at the boundaries. In addition, there are minimum depth, minimum altitude and maximum depth constraints. The mission planner must generate plans that the vehicle can achieve so that the vehicle maintains the safe trajectory determined by the planner. The intent is for this to happen with the planner having minimal knowledge of the vehicle's dynamics. It should be able to function using only rudimentary factors such as turning radius, and allowable speed ranges.

When the mission planner is in control of the vehicle, surfacing of the vehicle is only allowed at previously identified safe regions (surface stovepipes) and requires a permission signal from the host ship to prevent the vehicle from surfacing into heavy traffic areas. Surface stovepipes are locations where it is safe for the vehicle to surface and are specified by the user.

Naturally, the planner must operate in a real-time environment. That is, it must take information from the ahead-look sonar, process the data, evaluate possible plans and select and implement a plan in time to maneuver the vehicle along a safe trajectory

The planner framework needed to have the capability to receive asynchronous input from both the sonar system and the host ship. The sonar system sends terrain and target data to the planner asynchronously but can also request that the planner take an acoustic image of a specified target or that the vehicle perform a depth excursion to sample the water column.

If the operator needs to override the planner and terminate the mission in a controlled manner, a request can be sent to the planner. Upon receiving such a request, the planner will smoothly transition to the end mission activity which will surface the vehicle in a pre-specified location that is assumed to be free of boat traffic.

Any effective software system should have a simple, intuitive interface. In the case of the mission planner, this applies to the specification of mission objectives as well as feedback during the mission. To simplify the input required to execute a mission and to provide modularity, the planner input consisted of high level mission objectives. These objectives were specified in the form of high level activities and their associated mission utility. A brief description of the activities implemented for the AMMT mission planner is provided in the next subsection.

A. AMMT Mission Activities

The mission planner uses preplanned and contingent activity input specifications to determine the vehicle trajectory. The mission planner will always attempt to complete all preplanned activities within resource constraints. The contingent activities are different from the preplanned activities in that the mission planner does not consider their inclusion in the plan unless a predetermined set of conditions is satisfied and including the activity increases the overall value of the mission.

Each preplanned activity may have ordering constraints which restrict its position in the plan relative to other activities.

The number of times each contingent activity is considered for inclusion in the mission plan is limited to the specified maximum number of times that it is allowed to occur during the mission. In addition, contingent activities may also have ordering constraints which restrict where they can be inserted in the plan.

Start Mission

The Start Mission activity is used to command the vehicle to leave the surface, attain start up depth and power up any necessary equipment.

Transit

The Transit activity is used to command the vehicle to a specified waypoint. If obstacles or terrain prevent the vehicle from reaching the specified point, it will approach the point as closely as possible.

Survey

The Survey activity is used to search a region defined by a convex polygon. A mode parameter selects the survey search pattern, either a comb search or a survey area perimeter search.

Data Upload

The Data Upload activity is used to maneuver the vehicle to permit acoustic transmission of data files (image or map data) to a distant host ship.

Sensor Image Point

The Sensor Image Point activity is used to image a particular point using either acoustic or optical imaging. The vehicle follows a track specified by a length and azimuth. If the mode is optical, the specified track is centered about the point. If mode is acoustic, the specified track ends at the point.

For optical imaging, the planner will command the vehicle to drive over the ground track at constant pitch if terrain following is specified. The planner will trigger the optical imaging device when the vehicle is above the commanded latitude and longitude.

Depth Excursion

The Depth Excursion activity is used to sample the water column using any onboard environmental sensors. The vehicle drives to the commanded latitude and longitude while obtaining the minimum testbox depth and commanded speed. After having reached the commanded position and minimum testbox depth, it will then drive to the minimum altitude. The

vehicle will use ballast and propulsion systems to maneuver in the water column.

GPS Navigation Fix

The GPS Navigation Fix activity is used to obtain a GPS position fix, which requires the vehicle to be on the surface. The vehicle drives to the selected surface stovepipe and requests permission to surface. Upon receipt of permission or passage of a time-out period to pass, the vehicle will surface under ballast control. Once on the surface, the vehicle will wait for either the standard deviation of the navigation error to decrease below the specified completion accuracy or for a time-out to pass.

End Mission

The End Mission activity is used to terminate the mission at the specified location. The vehicle maneuvers to the commanded location at minimum depth, stops and requests permission to surface. Upon receipt of permission or passage of a time-out period, the vehicle will surface under ballast control.

Contingent Sensor Image Target

The Contingent Sensor Image Target activity is used to optically or acoustically image discovered targets. In either case, the target must be within an allowable imaging region (defined by a latitude, longitude, and radius) and there must be a feasible groundtrack (considering obstacles and maneuvering constraints) to obtain target imagery. The approach azimuth to the target is determined by the mission planner.

For acoustic imagery, the activity is triggered when the sonar/mapping system requests it. For optical imagery, the activity is triggered when there is a target meeting the threshold criteria of minelike probability level and signal to noise ratio.

Contingent Depth Excursion

The Contingent Depth Excursion activity is used to sample the water column using any available onboard environmental sensors and is requested by vehicle subsystems. This activity will be performed in the vicinity of the vehicle's position at the time of the request.

Contingent GPS Navigation Fix

The Contingent GPS Navigation Fix activity is used to obtain a position fix when the navigation error has grown too large.

III. System Design

This section provides an introduction to the design of the mission planner. The design of the planner is a *hierarchical* one where the planning problem is decomposed into smaller problems that can be solved with the time and information available. This design also leads to a modular architecture so the planner and plan management functions are separate from domain specifics such as the individual mission activities and the mission database. The architecture was implemented in a priority based, real-time UNIX environment.

A *graphical user interface* was developed to assist the operator in developing the planner's activity input file and to provide an interface to the pre-mission planner. The *Pre-mission planner* was used to ensure that the activity file, based on a priori environmental information, is feasible and desirable.

Most activities are to be performed at a commanded altitude. The *terrain following* planner is used to generate a depth profile that will allow the vehicle to closely follow the desired altitude while maintaining vehicle safety. It must take into account vehicle maneuverability in the presence of varying terrain.

If the operator needs to *override* the planner and terminate the mission in a controlled manner, a request can be sent to the planner. Upon receiving such a request, the planner will smoothly transition to the end mission activity which will surface the vehicle in a pre-specified location that is assumed to be free of boat traffic.

A. Hierarchical Planner

The mission planner decomposes the problem hierarchically into problems that can be solved quickly. The hierarchy has three levels. At the highest level are the mission activities as specified by the operator. The top level planner uses low fidelity estimates of resource consumption and the vehicle state to determine the sequence of activities that maximizes the objective in an expected value sense. At lower levels in the hierarchy, the estimates become more refined and this data is aggregated and fed back to the higher levels. For each level in the hierarchy, there exist a set of activities at that level and a pair of functions associated with each level. The first function is an estimator of the resources needed to complete the activity and the vehicle state at the end of the activity. The second function is used to expand an activity into a sequence of more detailed activities at the next lowest level. This architecture provides for a plug-and-play capability because the planner itself does not need to know the details of a mission activity.

As an example, consider the task of obtaining a GPS fix which is illustrated in Figure 1. The top level planner uses an estimator that does not take into account details of the activity. Using the estimated state of the vehicle at the start of the activity, it computes a crude estimate of the resources needed to complete the task and estimates the vehicle state at the end of the activity. The top level planner uses this information to insert the activity in the plan. This top level activity is then broken up into five, more detailed, activities. The vehicle must first transit to the stovepipe, request permission to surface, surface the vehicle, actually get the fix and ballast down. Each of these activities are able to make a more refined estimate of the resources needed. For example, the transit activity can use knowledge of the ocean current and terrain to get a precise estimate of the time and fuel needed to

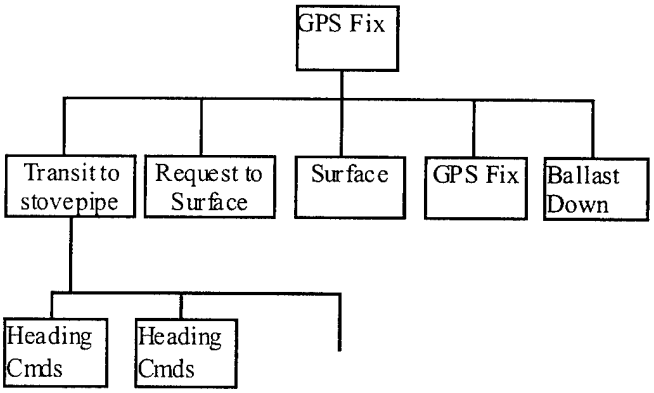


Figure 1: Decomposition of a GPS Fix

get to the stovepipe. The sum of each of the estimates at this level are then used to refine the top level estimate which may cause the top level planner to resequence its activities and start the process over.

At the highest two levels of the planner, the problem is one of sequencing the activities at that level. This is a difficult combinatorial problem because the set of feasible sequences is quite large even for missions of moderate size. Instead of trying to find the optimal sequence of activities, a heuristic, simulated annealing based approach was used.

At the third and lowest level of the hierarchy, the problem becomes one of path planning. Path planning encompasses planning in both the horizontal and vertical planes. The planner first determines a plan in the horizontal plane. This is accomplished with an A-Star search which takes into account the present state of the map and the estimated ocean current. The terrain following planner then finds the path in the vertical plane.

B. Task Descriptions

The mission planner was implemented in a real-time, priority based UNIX environment. The planner consisted of four tasks. They were:

1) Mission Planner
2) Mission Evaluator
3) Guidance Interface
4) Asynchronous Input Handler

The Mission Planner task operated at the lowest priority and was responsible for sequencing the activities of a single level in the hierarchy. It would consider permutations of the current plan to see if it could do better. It would only consider permutations which preserved the ordering constraints for the mission. It would also attempt to add contingent activities to the plan if their trigger conditions had been met. This task was not aware of the details of the activities or their trigger conditions.

The Mission Evaluator incorporates the output from the Planner task into the currently executing plan. It also controls the input to the planner. This input includes which level the planner task should be working with and when it should restart the planning process. Its most important job was to verify the safety and the feasibility of the currently executing plan. If it determined that the environmental conditions had changed so much that the current plan was no longer safe, it would invoke an immediate replan or provide reactive measures for the near term.

The Guidance Interface operated at the highest priority and was the planner's only interface with the fault tolerant processor. This task had to convert the "executing" activity into a guidance command that the vehicle's guidance system could understand. It also monitored subsystem health, controlled subsystems and read environmental sensors.

The Asynchronous Input Handler was responsible for processing terrain and target messages and updating the map. Moreover, it would respond to requests from the sonar and the host ship.

C. GUI/Pre-mission planner

A Graphical User Interface (GUI) was developed to support the Mission Planner development and was used at sea by the Test Director in defining the missions to be run. The GUI was developed using TCL/TK, a platform-independent scripting and graphic user interface development language . The GUI provides a front-end for generating activity lists which are then input to the pre-mission planner. The GUI has a number of tools designed to simplify the design of an activity list and to ensure that its output adheres to the specification The use of a configuration file allows changes to the specification (e.g., new activities, changes to parameter ranges) to be quickly reflected in the operational GUI.

Figures 2 and 3 show the two primary GUI windows for the mission run in the field on April 24th, 1996. Mission specification, Figure 2, has four major components: 1) pull down menus along the top (e.g., the preplanned activities menu is shown as a tear off); 2) three boxes listing all the global, preplanned, and contingent activities, if any, respectively; 3) a data entry area for editing the parameters of one selected activity at a time; and 4) a set of buttons that affect components 2 and 3 above. This window is used for entering all non-graphical activity parameters (the graphical parameters can be entered as well), viewing the parameters of all activities of a mission list, deleting and reordering activities, assigning ordering constraints, verifying activity parameters.

Mission Display, Figure 3, presents a graphical view of the mission list, which has 3 parts: 1) pull down menus along the top; 2) graphical display area; and 3) a set of displays and buttons. This window is used for defining graphical activity parameters (e.g., the figure shows the new seven sided survey region ready for addition to the activity list); viewing all mission activities including the white Operating Area and green Testbox; and displaying the trajectory output from the pre-mission planner as an overlay

After the activity file is created with the GUI, it is sent to the pre-mission planner. The pre-mission planner is used to ensure that the activity file, based on a priori environmental information, is feasible and desirable. It is a replica of the code executing in the planner and evaluator tasks and generates a baseline plan based on any avoidance stovepipes in the activity file. Based on this, a trajectory generator function outputs vehicle operating speed, operating depth or altitude, heading and fuel consumption that is overlaid on the GUI output. The operator can also specify an a priori map and ocean current estimate that can also be included in the baseline plan. The combination of the GUI and the pre-mission planner was an invaluable tool in the field test. This allowed for positioning of the host ship during the missions and accurate estimates of mission duration.

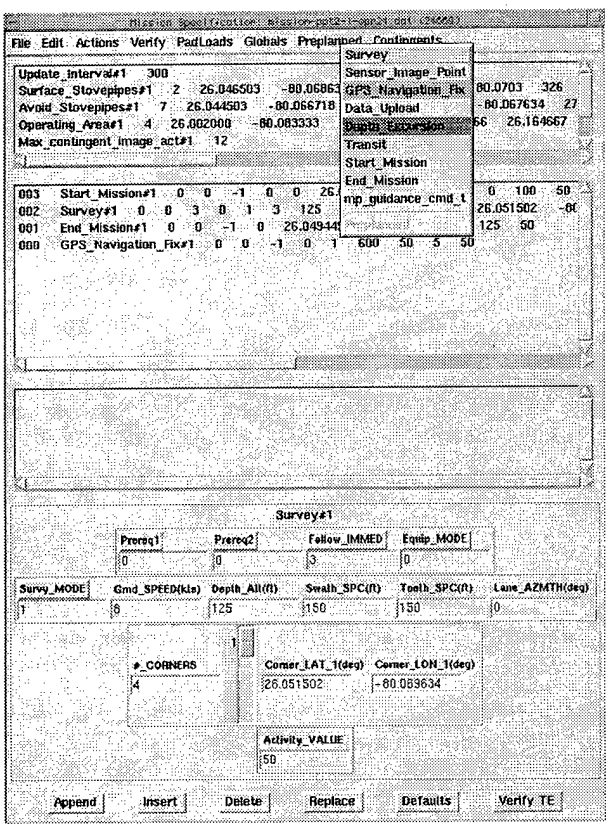


Figure 2: Mission Specification

D. Terrain Following

The terrain following (TF) process supports the mission planning requirements of real-time plan generation, safe plan generation, and the creation of achievable plans. TF is called with down track terrain depth information and outputs the depth profile that will allow the UUV to best follow this terrain at a commanded height above bottom. For most useful missions, this process is more complicated than simply adding the commanded altitude to each of the terrain depths, because the vehicle dynamics need to be considered in

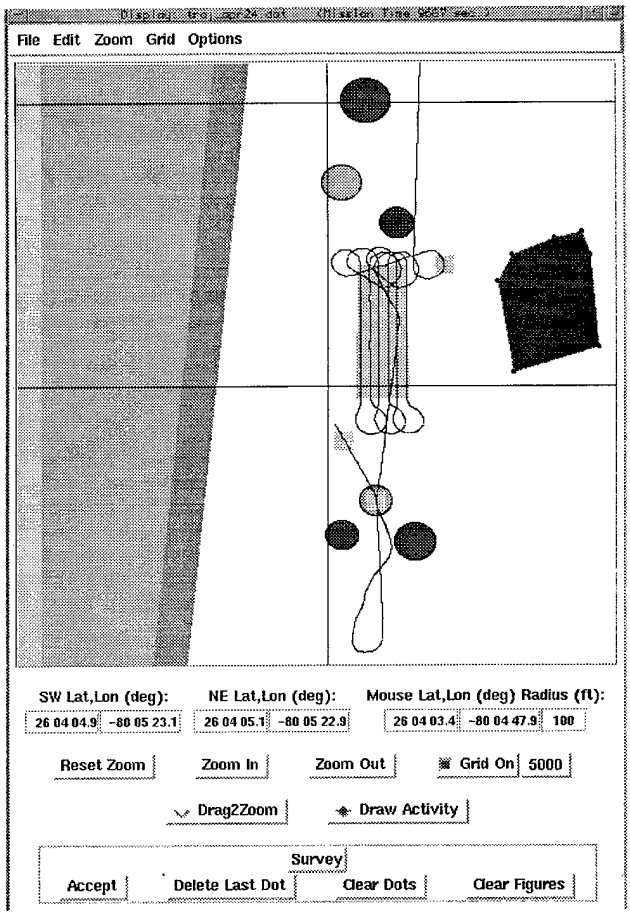


Figure 3: Mission Display

order to produce a flyable trajectory. Figure 4, which illustrates the role TF planning plays, shows terrain in gray, a dashed gray trajectory exactly offset by the commanded altitude, and a solid black TF plan that includes vehicle dynamics. The figure highlights some of the tradeoffs that the TF planner makes in trying to remain at a commanded altitude, while accounting for vehicle capabilities, as follows:

•The TF plan smoothes through the high frequency terrain at A

•Positive pitch limit requires an early climb in order to clear the peak at B

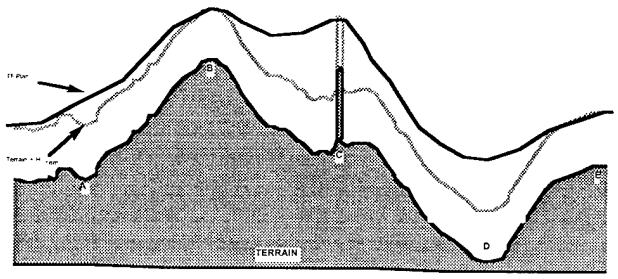


Figure 4: TF Planning Example

•Vehicle cannot follow altitude too closely from B–C in order to properly clear pinnacle obstacle at C.

•Vehicle cannot dive too deeply from C–D in order to clear peak at E.

The Terrain Following software is organized into two major pieces: Plan Generation and Plan Access. Plan generation is called at a relatively low rate with the goal of providing a vertical trajectory for the next segments of the horizontal plan. Plan generation accepts the current vehicle state and arrays describing the terrain over which TF plan is desired, and the routine outputs the depth and pitch commands (i.e., the TF plan) to properly traverse the terrain. TF plan access is called at a high rate to provide the appropriate depth and pitch command from the active TF plan given the vehicle's current state.

IV. Implementation Issues and Results

This section reviews implementation issues that were faced in implementing the planner as well as results from the at sea test runs of the planner. During the test program, the planner successfully controlled the vehicle for missions up to six hours in length.

This section is divided into subsections that address issues in 1) real-time performance 2)The ability to be robust to low quality sensor data 3) the ability to generate safe plans and 4) the ability to create plans that were achievable with respect to the vehicle's control system.

A. Real-time Performance

Generating plans in real-time can cause difficulty in two areas. First, when the planner must expand a node in its hierarchy (e.g., when it calls the path planner to generate a detailed trajectory), this function must complete before the trajectory is to be executed. Second, if the current plan suddenly becomes unsafe, the planner must be able to replan quickly so as to keep the vehicle in tact. These problems were addressed at three levels:

Time bounds on the path planner. Time bounds were based on the time remaining in the plan. The planner needed to return before this time, with any safe plan it had found (even if this is a partial plan). If no plan was returned, it would try again in hopes that more map data had been collected. To decrease the chance of this happening, path planning problems were broken up into small pieces. The design of the planning algorithm makes it more amenable to solving many small problems than one large one.

Emergency trajectories. In an attempt to limit the number of situations where the path planner would time-out, the planner would attempt to insure that there was sufficient time to plan. If a plan was needed in less than 30 seconds, a *reactionary* planner would be called to find an interim plan. This planner would only be concerned with finding a 30 second trajectory that avoided obstacles, so it was very fast. The results of the reactionary planner would be appended to the current plan and then the path planner would be called.

FTP time-out. As a final safety net, the fault tolerant processor would monitor the activity of the mission planner. If the planner did not send a guidance command within 10 seconds after completion of the last guidance command, the FTP would assume control of the vehicle and surface it. While this feature was successfully tested in the simulation lab, it was never needed at sea.

While the above features enabled the planner to generate plans quickly, they did sacrifice optimality. For example, since the plans for the path planner were decomposed, optimal trajectories were not always produced. Consider the ground track in Figure 5. To plan for the eastern track of the survey, the planner first found a path to the from the current position to the southern end of the track. This path planning problem did not have knowledge of the future track, so the vehicle was not properly aligned. The solution from the next call to the path planner had to begin with a loop to align the heading. If the planner did not decompose the problem for the sake of fast run times, this loop could have been avoided. Additional planner design beyond the scope of AMMT would find trajectories that are closer to optimal while not sacrificing reliability.

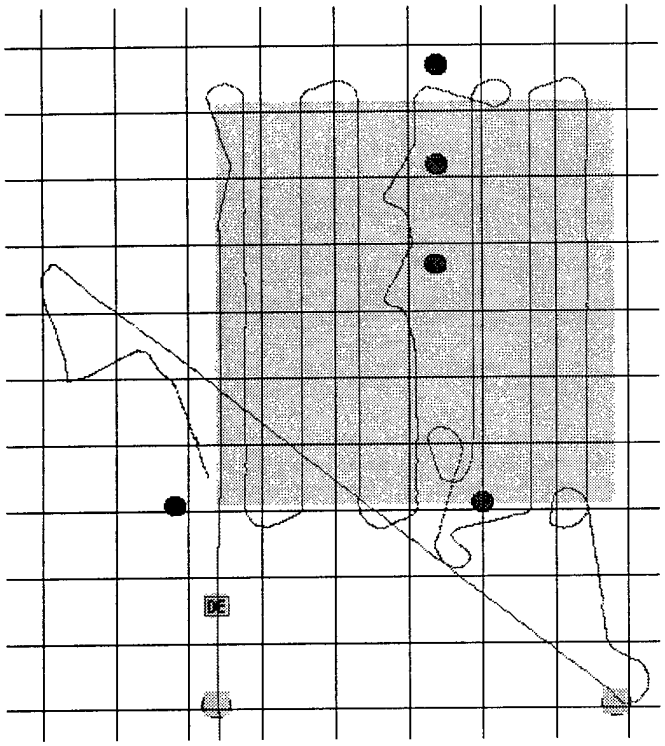


Figure 5: Actual Ground Track Overlaid on Mission Specification

B. Sensor Data Quality

Real time vertical trajectory generation is provided by a combination of terrain following and altitude following. Altitude following is simpler and more reliable in benign testing environments as it is not dependent on the quality of the ahead look sensor. However, altitude following is more sensitive to local terrain variations and will not be appropriate in more stressing environments where the vehicle must accommodate steep slopes by pitching up well in advance of the changing terrain. Terrain following outperforms altitude following in stressing environments, following at low altitude, and following at a fixed pitch. In all these cases, however, terrain following performance is reliant on the quality of the terrain data. To account for this, the planner would switch from terrain following to altitude following if the quality of the terrain data degraded. This is discussed in more detail in the next subsection.

In all planning problems, there are times when no valid plan is available. In this planner implementation, it is possible to get in this situation at the start of the mission. To protect the vehicle's safety, the planner would not travel to areas for which it had no knowledge of the terrain. For launches with no a priori terrain map, this implied that it could not travel until the sonar started operating. This was compensated for in the following way. After the vehicle was

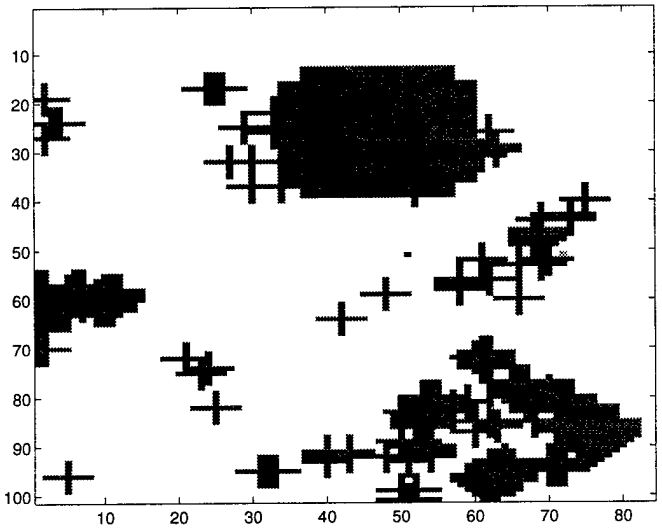


Figure 6: Map Built on April 24, 1996

launched, the planner would direct it to travel to the starting point of the mission at a pre-defined *safe depth* without doing any obstacle avoidance. During this journey, the sonar system would send the planner terrain data so upon reaching the start mission waypoint, the planner could dive to the pre-defined depth/altitude and begin obstacle avoidance. This method was not without shortcomings. If the sonar did not provide adequate data during the transit to the start point, the planner could find itself without a feasible trajectory. Consider the data in Figure 6, from April 24. The figure shows the state of the planner map upon reaching the start point. Cells that are shaded contain either a terrain or target obstacle and appropriate padding has been applied (this is discussed in the next subsection). The figure's coordinates are the 30 foot map grids with unsafe cells shaded red. The vehicle completed startup at the cell with coordinates (72,51). At that point, the vehicle was orientated north (the top of the figure) and needed to maneuver while avoiding obstacles to cell (51,51). It could not find any path so, in this case, it was not able to begin the mission. In future programs, the planner should be more adaptive to this type of scenario. Assuming that the vehicle is launched in a benign area, the planner should begin using altitude following in an attempt to gather more terrain data.

C. Safe Plan Generation

The mission planner is responsible for generating vehicle trajectories that are safe. Safe trajectories are trajectories that 1) avoid obstacles, 2) maintain testbox constraints and 3) respond to sonar terrain data dropouts.

Obstacles consist of both terrain and target obstacles. To avoid terrain obstacles, the planner maintains a map by smoothing the terrain estimates received from the sonar system. The granularity of the map is 30 foot square grid.

For each grid, the planner maintains an estimate of the mean terrain depth and variance. The planner assumes a normal distribution of the terrain which would imply that with 95% probability, the depth will be deeper than the mean estimate minus 1.6 standard deviations. This is the terrain estimate that is used for the grid. The planner would then allow travel through that grid cell only if this depth were at least as large as the commanded depth. Any cell that had a terrain estimate less than the commanded depth was considered a terrain obstacle. To account for uncertainty in the terrain estimates and the navigation system, the planner would not get within three map cells of any terrain obstacle. The planner's map is initialized with every cell having a very large variance thus unsurveyed cells are considered obstacles.

While this conservative approach worked well in simulation, it was not functional at sea. The actual sonar data did not always provide complete coverage or consistent estimates so the planner perceived there to be far more terrain obstacles than actually existed. As an example, Figure 7 shows one row of the map built during a diagnostic tow test on April 12. This figure shows the depth estimates for adjacent 30 foot map cells along an east-west direction.

Since the test environment was a fairly level terrain, the planner used a technique that minimized the amount of unsurveyed areas. When the planner received an estimate for a given map cell, it would use that estimate for any *unsurveyed* cells within 100 feet of the estimate. This, along with additional smoothing, provided much more usable maps. When this technique was applied to the same data from April 12, the result is shown in Figure 8.

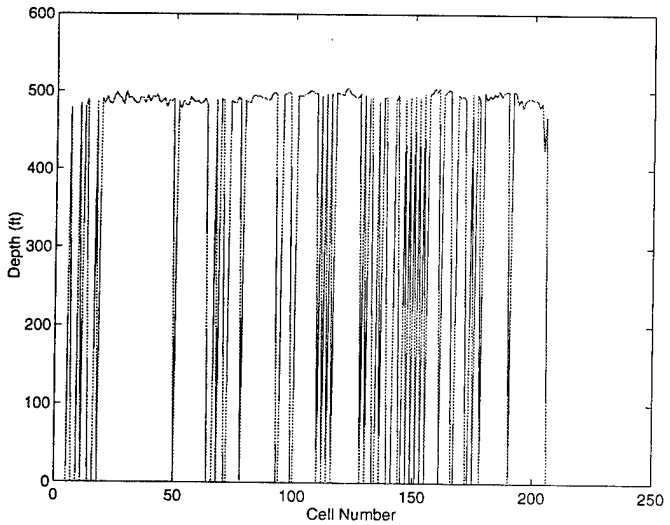


Figure 7: Depth Estimates

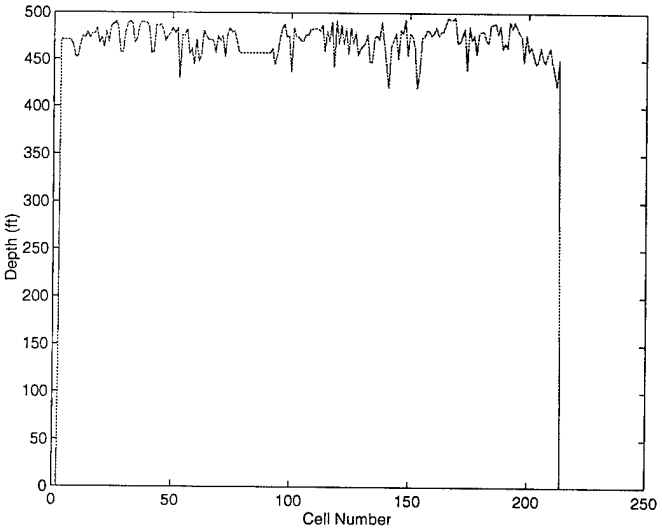


Figure 8: Depth Estimates of smoothed data

As the sonar system identifies possible targets, it notifies the mission planner. If the target is indicated as a tethered mine or some other obstacle that the vehicle should not pass through, the respective cell on the planner's map should be flagged as an obstacle. This applies to pre-planned avoidance stovepipes also. A grid cell is flagged as an obstacle by negating its depth estimate value; this preserves the depth estimate at that point. Future depth estimates are correctly incorporated but the path planner always views this cell as an obstacle. Once again, sonar, navigation and guidance uncertainty must be factored in, so the planner does not plan to get within 3 map cells of an unsafe. An example of a ground track that goes around a target was shown in Figure 5. The figure shows the effect of the padding around the target. In all of the at-sea trials, the vehicle avoided all terrain and target obstacles.

The mission planner is required to keep the vehicle within a three dimensional testbox at all times. The only exceptions are when the vehicle surfaces for a GPS fix. The testbox is specified as a East and West longitude boundaries, North and South latitude, minimum and maximum depth and a minimum altitude. If the planner should command the vehicle to leave the testbox, the FTP will take control of the vehicle.

The boundaries of the testbox in the horizontal plane are treated the same way as terrain obstacles so the planner will not exceed the latitude or longitude boundaries. Additionally, the planner does not consider any activities that are within 1000 feet of the edge of the testbox to prevent it from having problems turning near the edge of the testbox. As an additional safety margin, the mission planner's testbox is typically specified as being smaller than the FTP testbox for testing of the mission planner without risking mission abort.

The mission planner's depth and altitude limits are also more restrictive than the FTP limits to test the mission planner. This is needed to account for uncertainty in the sensors and because it is more difficult to control the vehicle vertically. Typically, the difference in the limits used in the mission planner and the FTP were on the order of 25-50 feet. After the test program, these values would be minimized When comparing the actual depth of the vehicle to the mission planner's depth limit, the difference was never more than 8 feet. The minimum altitude limit was never violated except for one data point during dive 6 of April 25 which was apparently a result of noise in the altimeter.

The planner is highly dependent on its map which is created from the terrain and target data that it receives from the sonar system. If this data should cease to become available, say, either because of a sonar malfunction or a data communication problem, the planner must take steps to preserve the safety of the vehicle. The planner's guidance task has been implemented to monitor the time since the last valid input from the sonar system. This threshold may be changed at runtime, but was typically set at 30 seconds. If the time since the last input exceeds this threshold, the planner assumes that there is a malfunction somewhere on the vehicle and does not trust its own map data any longer. If the planner was executing a depth command, it transitions to a safe depth in hopes of avoiding terrain obstacles. It continues to avoid any targets that it has been notified of. If the planner is executing an altitude command, it transitions from terrain following to altitude following. Monitoring the time since the last data input only ensures that some data is being received; it is not sufficient to test for valid terrain data. The planner actually monitors the time since the last *high quality* data message. Quality is defined as the ratio of valid data points to the total data points in the message; a high quality data message must be above this threshold.

By the time the planner starts receiving valid data messages again, the vehicle might have traveled to a previously unmapped area. To provide for a smooth transition back to terrain obstacle avoidance, the operator can specify the number of good data messages that must be received before the planner starts working with the map again. This value was typically set to 30 seconds.

D. Achievable Plans

An additional artifact of the requirement to operate in real-time is that the planner must plan with the dynamics of the ocean current. The planner maintained an estimate of the ocean current based on filtered measurements of groundspeed and estimates of waterspeed. This estimate was used both to estimate the time and energy needed for an activity as well as in path planning. The path planner would often need to find a path that maintained a constant ground speed. If the planner ignored the effects from the ocean current, many of the trajectories it created would not be achievable because they dictate a waterspeed outside of the vehicle's range. By explicitly planning with the ocean current, the planner was able to generate trajectories that could actually be achieved. This was critical in generating safe plans

The mission planner must generate plans that the vehicle can achieve so that the vehicle maintains the safe trajectory determined by the planner. At the same time, the intent was to build a planner that could easily be transferred to other vehicles. Moreover, in order to meet the real-time goals, the path planner could not model all details of the vehicle's capability and guidance functions. The planner only had knowledge of the vehicle's turning diameter, water speed limits, pitch limits and the ocean current estimate.

To estimate the ocean current, the planner used a two stage process. The planner filtered the ground speed estimates from the navigation system to have a smooth estimate of the current. At the time of path planning, this estimate would be used to get a safe trajectory and the estimate would be stored with the trajectory. When a part of that trajectory was to be executed, the planner would compare the present current estimate with the estimate used in planning and modify the water speed or yaw rate appropriately. This second correction proved to be useful as the current changed quickly. Figure 9 compares the planned versus actual ocean current for a 4500 second period on May 3. Figure 10 compares, for that same time period, the planned water speed with the commanded waterspeed after the change in current was taken into account. Without this process, the generated plans would not always be achievable without violating the vehicle's water speed limits.

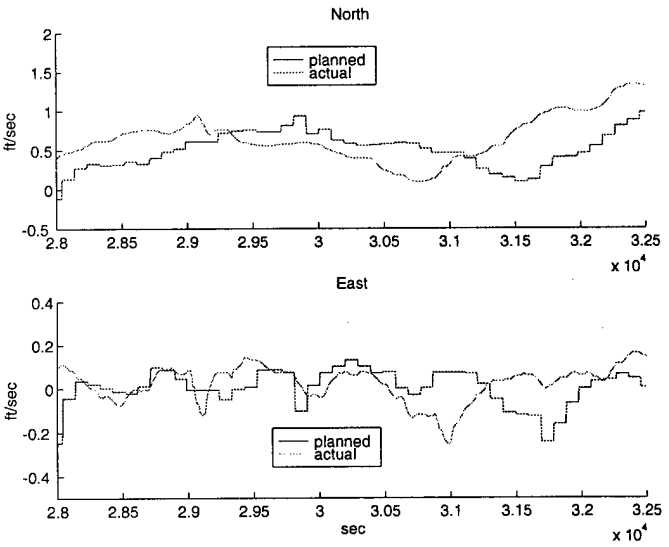


Figure 9: Ocean current from May 3

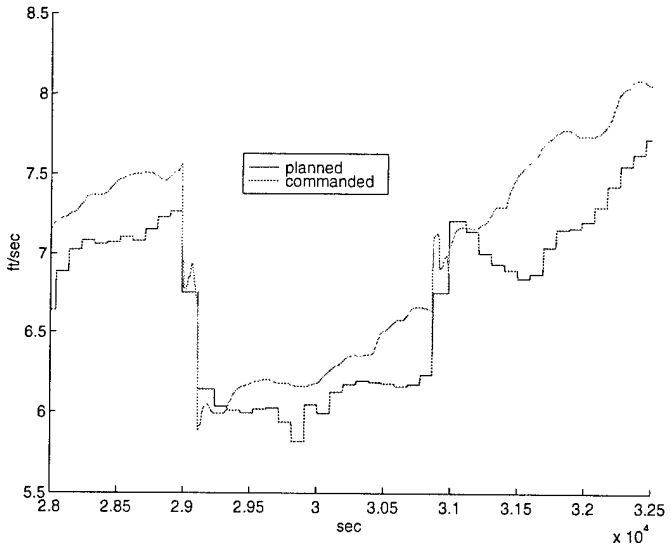


Figure 10: Speed comparison

The planner was successful at creating trajectories that were achievable by the actual vehicle. The vehicle's actual groundtrack was compared with the planned trajectory and the differences were logged. The errors were recorded in both the direction of the vehicle's path and perpendicular to the vehicle. The perpendicular error has a greater effect on the safety of the vehicle. The median of the magnitude of the errors for all of the autonomous missions at sea was 2.9443 feet for the perpendicular error and 0.000061 feet for the along error. In the case of a survey, the error was not as critical during turns. Effort was concentrated on minimizing the error during straight legs of the survey to provide accurate mine mapping. For the test program, the goal was to have the errors less than 50 feet during turns. For the same time period on May 3, the errors are plotted in Figure 11.

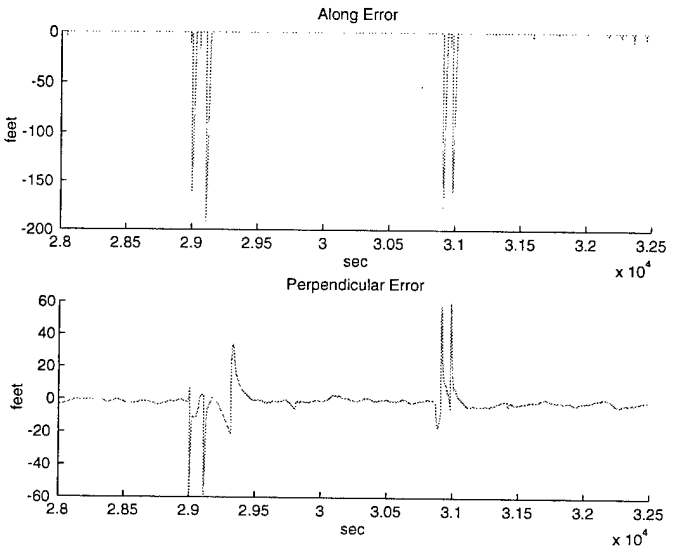


Figure 11: Distance Errors

V. Summary Areas for Future Research

The AMMT program demonstrated a real-time, on-line mission planning system to maneuver the vehicle to meet mission objectives. This capability supports the future needs of Unmanned Undersea Vehicles.

The planner successfully generated and executed mission plans in varying ocean environments. The vehicle was able to achieve the planned trajectory and to maintain safe operating conditions. The technical approach to planning in real-time was validated and areas of improvement were identified.

A number of issues beyond the scope of the AMMT program were recognized during development and testing of the program. The primary lesson is that even if planning was perfect and took no time at all, the system performance would only be as good as the data input into the planner. Therefore, continued development should occur in improving the quality of information in the planner map. Furthermore, for high system reliability, sophisticated subsystem health monitoring and control should be incorporated into the planner to maximize mission objectives during degraded operations.

Improvements in mission planning should also occur. Developing search algorithms that can produce feasible plans quickly will allow the planner to develop more optimal plans or plans with longer time horizons. Also, bootstrapping of the planner needs additional work. Early on in a mission, there is no feasible trajectory at the start of the mission. There is a chance that this can happen at any time based on the collected sensor data. Methods to accommodate this are likely to be dependent on the mission context.

An Integrated Ground and Aerial Robot System for UXO/Mine Detection

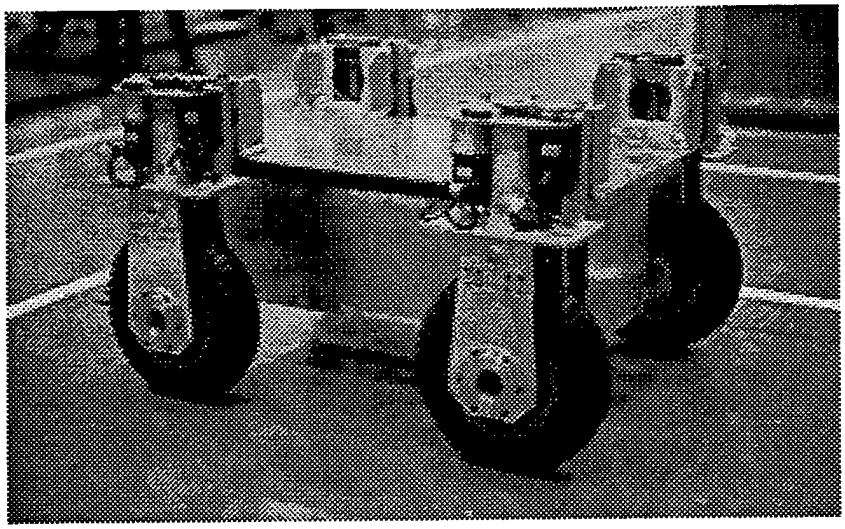
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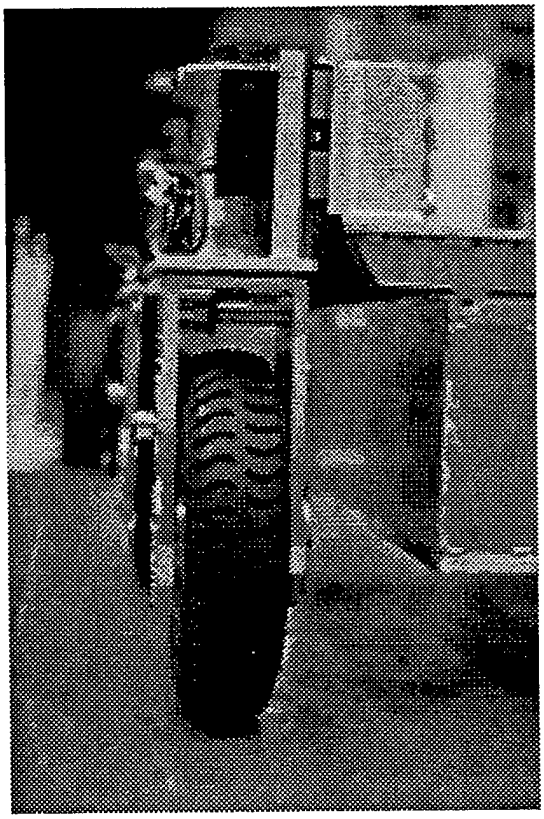
April 29, 1996

Abstract

This paper proposes a semi-autonomous robot system for land mine/UXO searching/processing tasks. The proposed robot system **consists of a land vehicle (called a *rotary vehicle*), an aerial vehicle and ground equipments**, where the two vehicles complementing each other to solve the difficulty of the mine processing tasks. **The unique feature of this system is a perfect coordinated tasks done by the two autonomous vehicles cannot do**: The land vehicle will do (1) detecting mines and UXOs in a small area, (2) processing a mine or marking the place if one is found, and (3) confirming absence of mines in an area if they do not exist. The aerial vehicle will do (1) global surveying, (2) evaluating the situation by observing the global situation, (3) guaranteeing a communication path between the ground system and the land vehicle. The coordination at this level is not attained by a system which has only one of these. Another major advantage of this proposal is that the rotary vehicle to be used here has a complete rotational degree of freedom, which will be extremely useful for the mine processing task. Use of the semi-autonomous robots for the task of eliminating the 100 million land mines planted all over is a far better concept than using human engineers and workers in a long run.

*Department of Computer Science
†Department of Aeronautics and Astronautics
‡Department of Electrical and Computer Engineering Department
§Department of Physics
¶Department of Computer Science





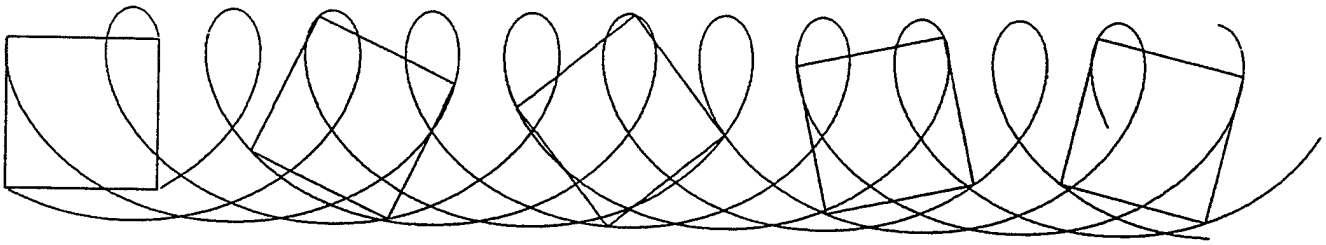


Figure 1: Rotary Vehicle Trajectory ($v = 20,\ \omega = 0.6$)

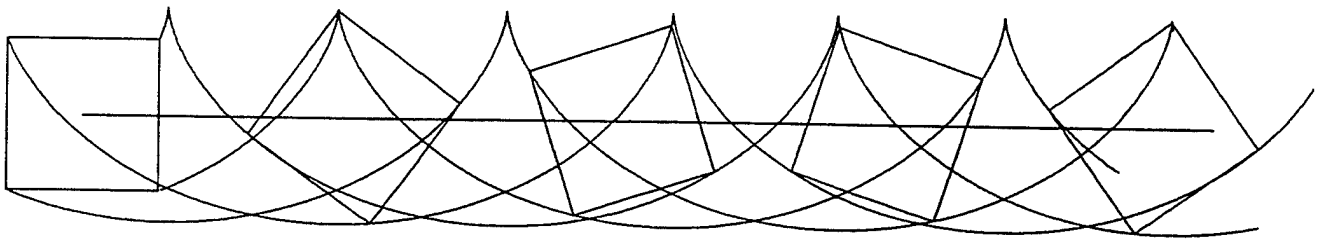


Figure 2: Rotary Vehicle Trajectory ($v = 20,\ \omega = 0.35355$)

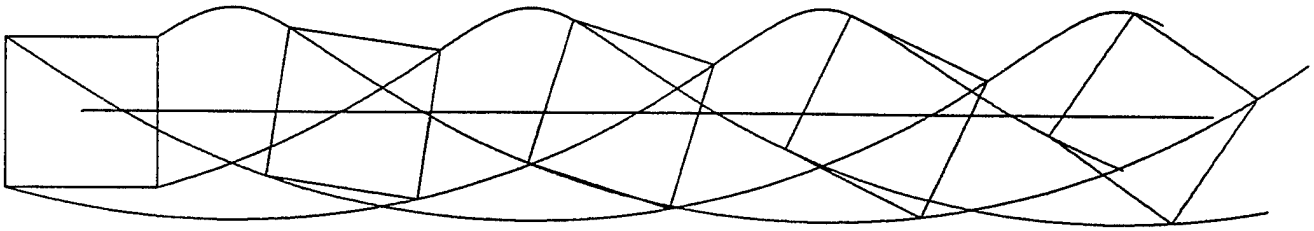
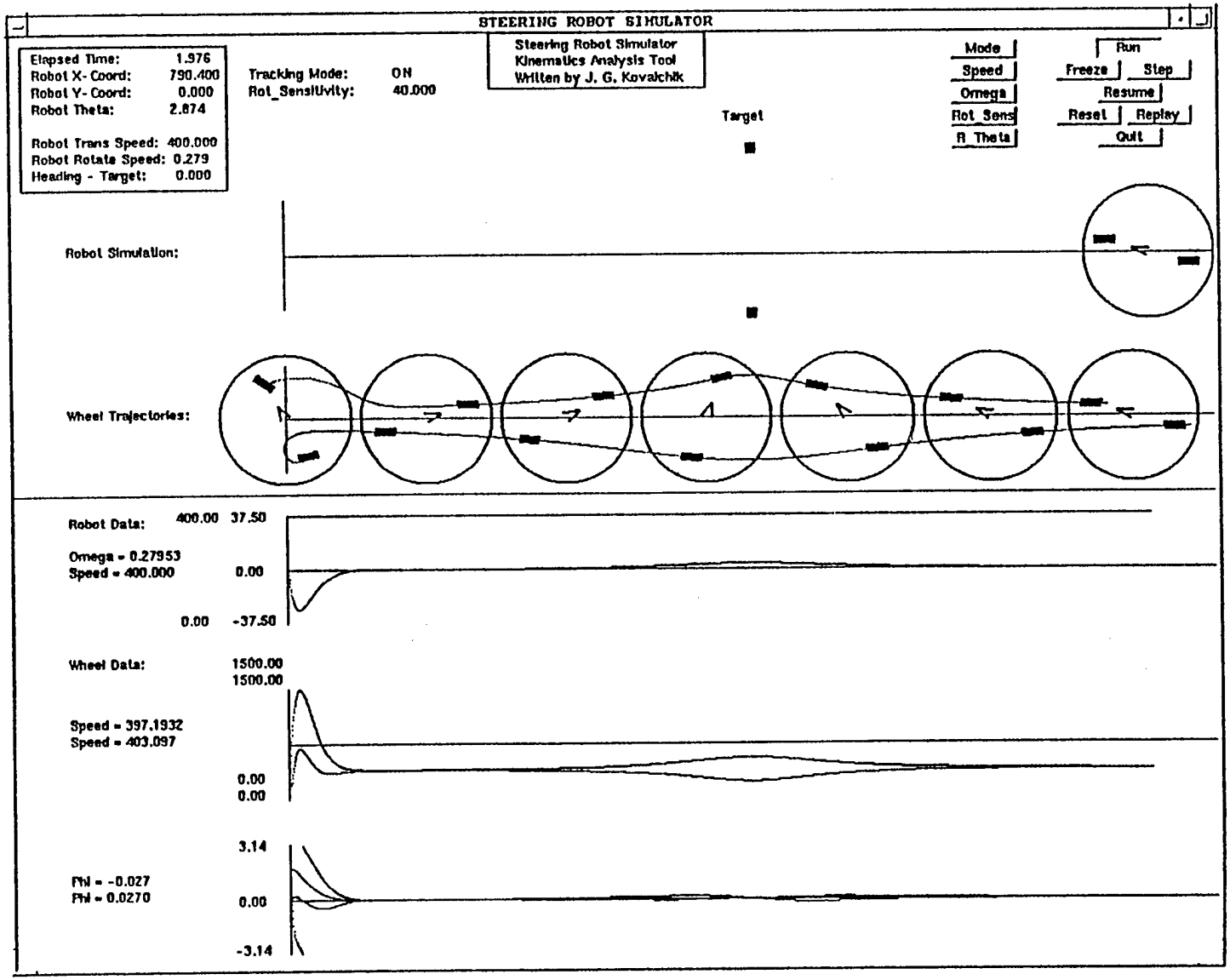


Figure 3: Rotary Vehicle Trajectory ($v = 20,\ \omega = 0.2$)


STEERING ROBOT SIMULATOR
Elapsed Time: 1.976
Robot X-Coord: 790.400
Robot Y-Coord: 0.000
Robot Theta: 2.874
Robot Trans Speed: 400.000
Robot Rotate Speed: 0.279
Heading - Target: 0.000
Tracking Mode: ON
Rot_Sensitivity: 40.000
Steering Robot Simulator
Kinematics Analysis Tool
Written by J. G. Kovalchik
Target
Mode
Speed
Omega
Rot_Sens
R Theta
Run
Freeze
Step
Resume
Reset
Replay
Quit
Robot Simulation:
Wheel Trajectories:
Robot Data:
400.00
37.50
Omega = 0.27953
Speed = 400.000
0.00
0.00
-37.50
Wheel Data:
1500.00
1500.00
Speed = 397.1932
Speed = 403.097
0.00
0.00
3.14
Phi = -0.027
Phi = 0.0270
0.00
-3.14

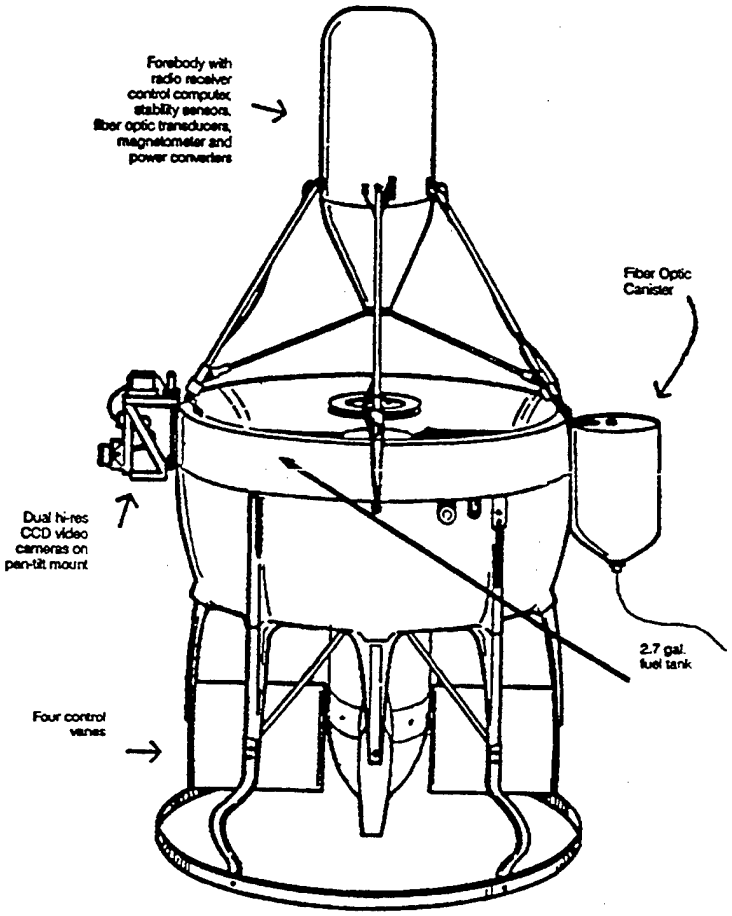


Figure 2.1: Airborne Remotely Operated Device, [Ref. Siu 91]

was not easily adaptable to anything other than the narrow range of conditions planned for AROD. The Sandia Labs papers also pointed out several types of coupling in the AROD. The most prominent of the coupling effects is the gyroscopic coupling between the pitch and yaw axes resulting from the large amount of angular momentum contributed to the aircraft by the propeller. Another dynamic coupling exists between the altitude–rate and the vehicle attitude, since a loss of lift due to thrust will occur when the vehicle is tilted to generate horizontal motion. Yet a third dynamic coupling exists between the altitude and roll control loops, since the reactive torques applied to the roll axis vary as the engine speed is varied. Sandia Labs also provided data for modeling both the engine and the servos as second order transfer functions which were used in this task.

Additional information was obtained by Weir [We 88] in wind tunnel testing. This information included non–dimensional derivatives for vane effectiveness and non–dimensional stability derivatives. The report also stated that the control–vane effectiveness is constant out to at least 25 deg of deflection. Wind tunnel data were also presented to show that

The Coastal Battlefield Reconnaissance and Analysis (COBRA) Program for Minefield Detection

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ABSTRACT

The Coastal Systems Station (CSS) at Panama City, FL is developing an airborne multispectral sensor system which flies on an unmanned aerial vehicle for detecting mines in a coastal environment. This system is called the Coastal Battlefield Reconnaissance and Analysis (COBRA) system and has successfully completed preliminary developmental testing (DT-0). For this program, the Environmental Research Institute of Michigan (ERIM) developed a fieldable ground station including integrated aircraft tracking, real-time sensor data analysis, and a post-processor test bed for developing and evaluating mine and minefield detection algorithms. A fully adaptive multispectral constant false alarm rate (CFAR) mine detection algorithm was implemented in the post-processor by ERIM, along with patterned and scatterable minefield detection algorithms developed by CSS. The algorithms do not require prior knowledge of mine spectral signatures and thus are ideal for detecting a wide variety of mines with unknown or changing spectral signatures. COBRA DT-0 testing has been performed on actual minefields deployed at coastal and inland test sites. Preliminary results show that the COBRA system, coupled with these algorithms, meets the program minefield detection performance goals. This paper describes the COBRA system and presents mine detection results from actual minefield imagery collected during DT-0 testing.

Keywords: multispectral, mine detection, minefield detection, unmanned aerial vehicle (UAV)

1.0 PROGRAM OVERVIEW

The COBRA program is a United States Marine Corps Advanced Technology Demonstration (ATD). The COBRA ATD objective is to design, develop, and demonstrate, in a Pioneer Unmanned Aerial Vehicle (UAV), a passive multispectral video based sensor system designed for automatic minefield detection. The imagery from the airborne subsystem will be processed in a ground station with algorithms to automatically detect minefields and to locate these detections. Obstacles, fortifications, and vehicles will be detected and located by human interpretation of the video imagery. COBRA is being developed for general beach reconnaissance from the surf zone to inland for use before and during an amphibious assault as well as for land combat operations in littoral areas. Figure 1 shows the COBRA system operational concept.

The Marine Corps Exploratory Development Program, Standoff Mine Detection Ground (SMDG)[1] demonstrated that video-based multispectral imaging sensors and appropriate image-processing techniques can provide a powerful, yet cost-effective, means for standoff mine detection. In Fiscal Year (FY) 1991, the SMDG program developed an experimental test bed using a video-based multispectral camera with custom optics for long- and short-range surveillance capabilities, specifically for mine detection. Using the test bed as the primary investigative tool, an extensive field testing program was conducted. The final test was an airborne test late in FY 92 where the test bed was flown in a UH-60 helicopter. Extensive multispectral imagery was collected, and a significant amount has been processed using Coastal Systems Station (CSS) developed image processing techniques to demonstrate mine detection proof of principle.

In FY 93, the SMDG program transitioned to the COBRA ATD program. In FY 93 a fundamental multispectral video test bed was flown in a Pioneer UAV at Pt. Mugu California to demonstrate the feasibility of performing beach reconnaissance in a UAV for minefield detection. With the UAV demonstration successfully completed, a complete redesign of the airborne subsystem was begun, along with developing a ground processing demonstration station. The system has now

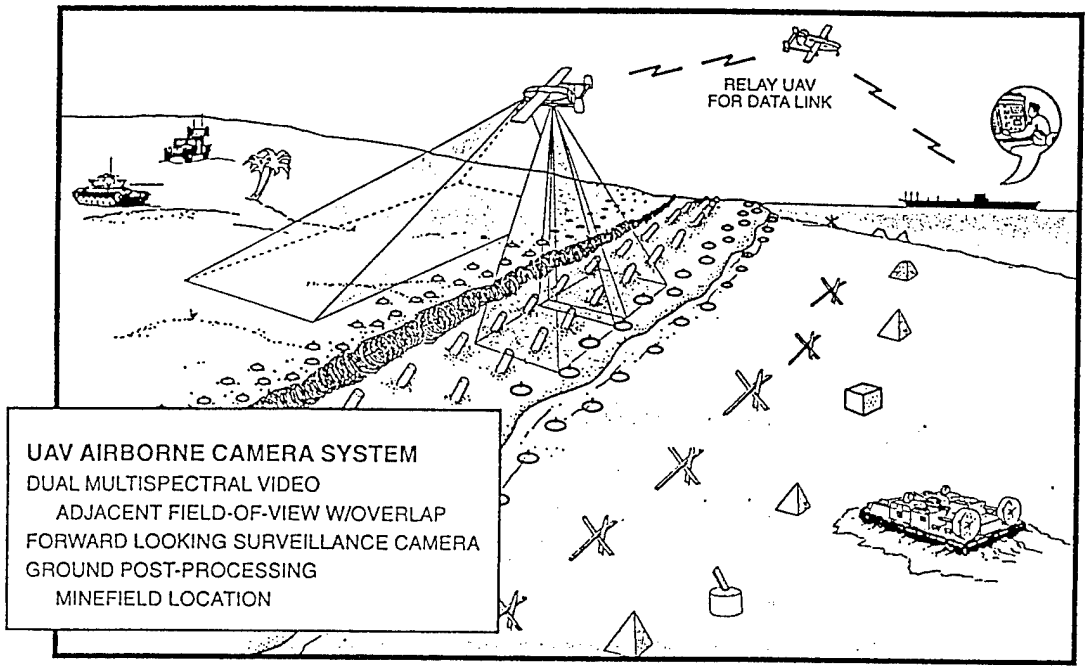


FIGURE 1. COBRA OPERATIONAL CONCEPT

undergone both preliminary developmental and operational testing. The remainder of this paper briefly describes the system, and presents recent testing results.

2.0 COBRA SYSTEM

The COBRA ATD system test bed includes an airborne passive multispectral video imaging subsystem for data collection and a ground station subsystem for real-time system tracking and post-mission processing. The COBRA airborne subsystem uses advanced multispectral video technology to image the ground scene for purposes of mine, minefield and obstacle detection along the beach from the surf zone to inland. Information on the aircraft heading, altitude, roll, and pitch will be combined with the aircraft Global Positioning System (GPS) position for location of all ground images. This information is encoded on the system video. During testing of the COBRA ATD system, as the aircraft is flying over the test site, limited real-time video is down linked to the ground station for real-time system assessment and tracking. All system data is recorded in the aircraft for automated minefield detection and location after tapes are returned from the mission. The COBRA functional system concept broken down by subsystems is shown in Figure 2.

2.1 COBRA AIRBORNE SUBSYSTEM

As the COBRA ATD system is being developed for UAV deployment for testing, it is critical to limit size, weight and power. Additionally, to minimize the costs, maximum use of nondevelopmental items will be made for concept demonstration. The use of a fast shuttered camera to eliminate ground motion blur removes the requirement for a stabilized platform, conserving weight and power. By using video cameras with standard RS-170 video output, commercial video products such as recorders, digitizers, and video links are readily available. Commercial lenses are not optimal for multispectral imaging which utilizes the full spectral range of the sensors; however, if properly selected, while still imposing performance limitations, commercial lenses are adequate to demonstrate capability. The multispectral bands, based on target/background characteristic, solar illumination, as well as system hardware limitations, are carefully selected to optimize performance. Figure 1, depicting the COBRA operational concept, shows the use of two multispectral cameras to increase the coverage swath and a forward looking surveillance camera to assist with the navigation and obstacle detection.

The COBRA airborne subsystem performs the collection, storage, and transmission of video data which includes the aircraft heading, altitude, attitude and position data which is encoded on each video stream. Data from each video sensor is recorded onto Hi-8 tapes for post-mission processing. During flight tests, selected data is video linked to the COBRA ground station subsystem for real-time tracking and system assessment.

The airborne subsystem consists of passive multispectral imaging components configured to output standard RS-170

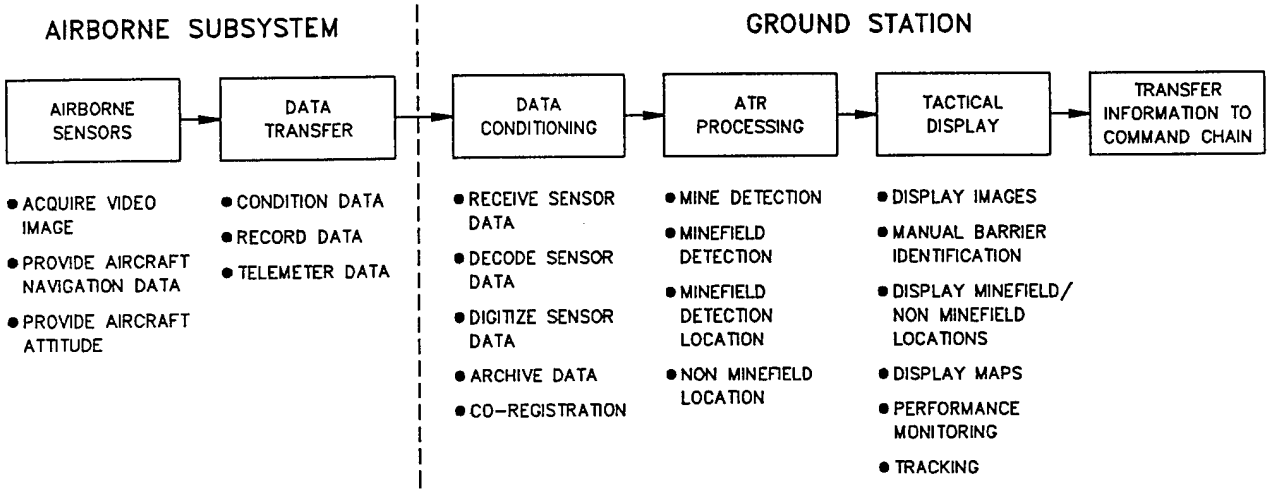


FIGURE 2. COBRA FUNCTIONAL SYSTEM CONCEPT

video. The video outputs are recorded on a Hi-8 mm, triple-deck recorder and simultaneously sent through a video switch to the Pioneer's downlink video transmitter. The major components are as follows: two multispectral video cameras, lenses, filter wheels, a surveillance video camera, Hi-8 triple-deck tape recorder, GPS receiver, attitude sensor package, altimeter, analog video link transmitter and other ancillary equipment including power conditioners and custom controller. The airborne imaging subsystem assemblies are mounted on a vibration isolation platform. Figure 3 shows the current COBRA ATD airborne subsystem concept.

The multispectral video sensor function is provided by two specially configured Xybion Model IMC-201 multispectral video cameras which are aligned to provide a double width swath as previously shown in Figure 1. Figure 4 is a diagram of a IMC-201 camera. The IMC-201 is intensified and gated for automatic exposure control. A spinning filter wheel is located between the camera lens and the imaging plane. The filter wheels are interchangeable and each contains six filters. The filter wheel rotation places a different filter in front of the camera imaging plane every 1/30th of a second which is the camera's frame rate. In this mode of operation, every video frame is a separate spectral band. The spectral range of the camera is from 400 nm to 900 nm. The intensifier, which allows for short exposure times through narrow spectral filters, does however, limit the spatial resolution. The camera functions are micro-processor controlled. The output from the camera is standard RS-170 interlaced video, which will be recorded on a Hi-8 video recorder. Select commercially available lenses used with this camera provide spatial and spectral resolution adequate for multispectral detection but limit the across all bands focus and optical throughput.

In order to locate any detections, the aircraft position, heading, altitude, roll and pitch are encoded on within each video image. In addition, camera information such as exposure time and gain settings, filter number, etc. are also encoded in each image. The aircraft GPS position information is encoded in Vertical Interval Time Code (VITC) in each video signal. All other information is encoded in bars along the left side of each image. The VITC and bar code data can be decoded in the ground station either during the flight or during the digitizing process after the tapes are received for processing. Using these encoding methods, a large amount of data is added to each image with minimal impact on the active area of the image.

2.2 GROUND STATION SUBSYSTEM

The COBRA airborne subsystem supplies video data to the ground station subsystem, referred to as the COBRA Tactical Information Display System (CTIDS). CTIDS was developed by the Environmental Research Institute of Michigan (ERIM) under contract to CSS. CTIDS performs two basic categories of operations: real-time functions during flight to provide an operator with sufficient information to validate proper sensor operation and to ensure required data is being collected, and post-mission functions using recorded mission data to detect minefields and report their location. The COBRA processing chain implements image analysis functions which currently operate on a near real-time (NRT) processor. The NRT processor will eventually be replaced with a processor capable

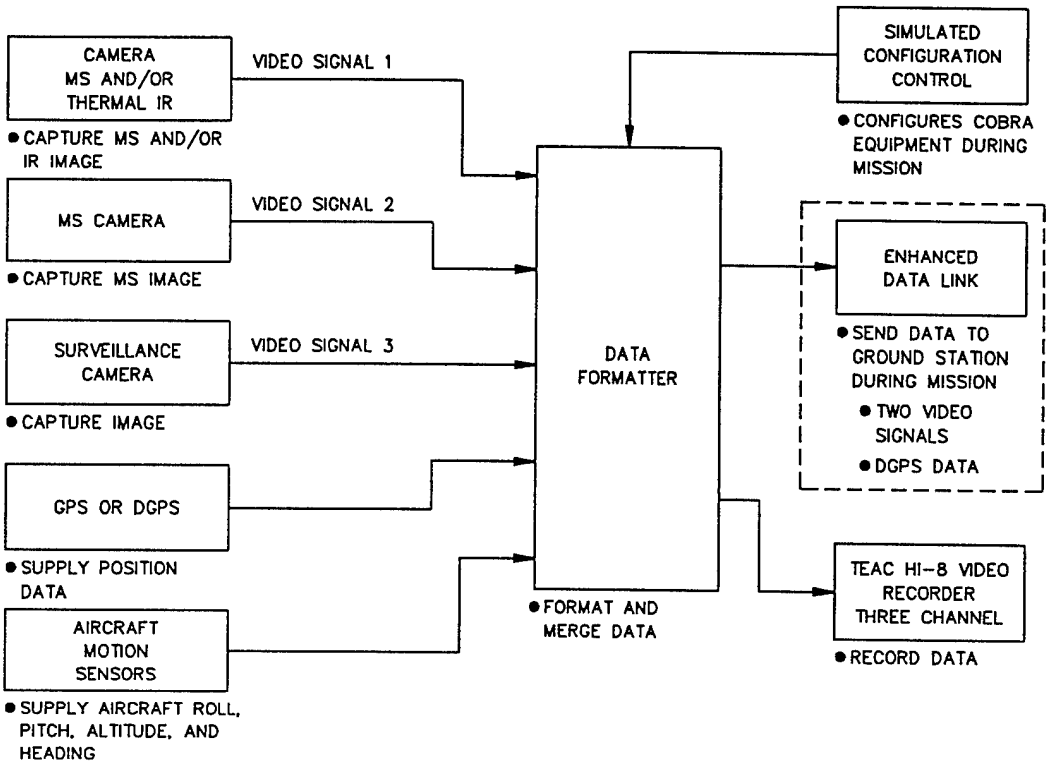


FIGURE 3. COBRA DT-0 AIRBORNE SUBSYSTEM CONCEPT

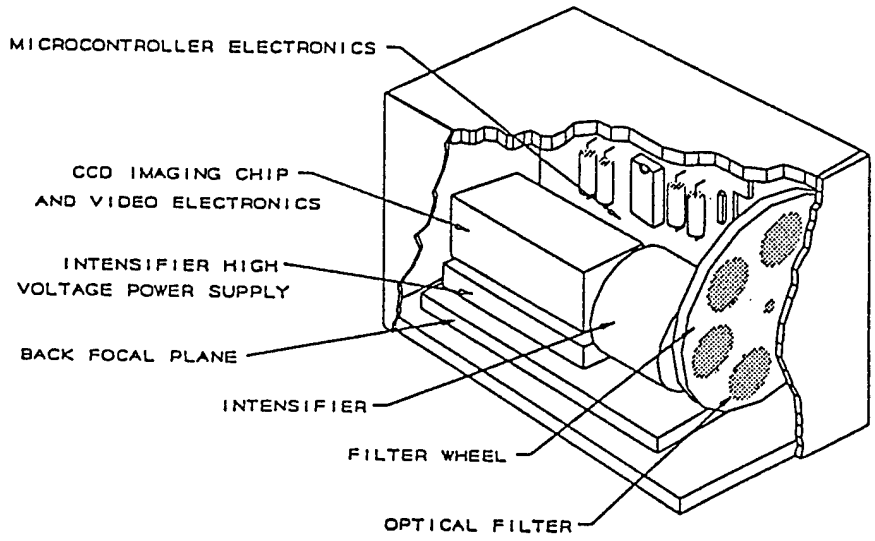


FIGURE 4. XYBION IMC-201 MULTISPECTRAL CAMERAS

of producing results in real-time. While there is no ATD requirement for the COBRA to perform automated minefield detection in real-time, the NRT processor was implemented so results can be achieved in a timely fashion to aid performance assessment during the formal testing phases of the program.

The CTIDS is organized according to these operations into the RTF subsystem and the NRT subsystem. The RTF provides CTIDS with the capability to record COBRA multispectral imagery from a real-time video downlink, digitize recorded imagery and archive images with required ancillary information. The RTF also provides video image review capability and analysis functions useful both during real-time operations for assessing flight operational effectiveness and sensor performance issues, as well as during post-mission operations for manual location of obstacles and fortifications. The RTF also displays real-time aircraft position updates overlayed on a variety of maps, satellite images, and other mission data for monitoring search patterns along with downlinked video imagery. The software can also be used to display and print final post-mission minefield detection results along the platform flight path.

The CTIDS NRT subsystem provides automated minefield detection using COBRA sensor imagery. Each spinning filter wheel multispectral video camera collects six bands of multispectral imagery sequentially at a camera frame rate of 30 Hz while in flight. Each of the six images are automatically registered for multispectral processing for minefield detection. ERIM developed an image-to-image registration algorithm[2] for COBRA which is capable of determining and performing complex coordinate transformation between images and subsequent image resampling to achieve subpixel registration accuracies. ERIM also implemented an adaptive multispectral Constant False Alarm Rate (CFAR) mine detection algorithm[2] which exploits spectral and spatial target signatures for automatic target detection. Once mine-like targets have been detected and located using data from the airborne video tapes, a linear density algorithm for patterned minefield detection[3] developed at CSS performs minefield detections. Capability is also incorporated for unpatterned (scattered) minefield detections using an algorithm originally developed under contract by The MITRE Corporation.[4] Besides automated detection, the operator also can use the video from the surveillance camera as well as the multispectral cameras for manual identification of obstacles. All detections, whether manual or automatic, are tagged with ancillary position, attitude and other information so that detections can be located and tapes automatically repositioned to raw imagery corresponding to the detections, if desired by the operator.

Because of the level of complexity of the COBRA processing chain, and the desire to not use specialized image processing hardware until the automated detection processing technology has been demonstrated, a high performance Sun UltraSPARC computer was used for CTIDS NRT processing. However, the RTF uses high-end personal computers making operation and maintenance of the system easier for a wider range of people. The COBRA ground station subsystem concept is shown in Figure 5. Figure 6 is a photograph of CTIDS. The CTIDS ground station subsystem includes a data link receiver, a ruggedized 486DX2-66 computer CTIDS controller, a 486DX-50 laptop computer and docking station for vehicle tracking, a Sun UltraSPARC processor computer for NRT processing, a computer controlled S-VHS recorder player, a video monitor, two color monitors and an Uninterruptible Power Supply (UPS).

3.0 COBRA PROGRAM STATUS

The COBRA Preliminary Design Review was held in September 1994 and the Critical Design Review was held in January 1995. Preliminary developmental testing (DT-0) was conducted at Eglin AFB, Florida and Camp Lejeune, North Carolina from May through August 1995. Preliminary operational testing (OT-0) is currently being conducted at Camp Lejeune during November 1996. The COBRA system is meeting or exceeding ATD goals in all background environments tested to date. COBRA will demonstrate is operational utility, along with other countermine systems, as part of the Joint Countermine Advanced Concept Technology Demonstration (ACTD) in FY 97 AND FY 98.

4.0 DEVELOPMENTAL TESTING

Preliminary developmental testing (DT-0) was performed according to an official COBRA DT-0 Test Plan developed by CSS and approved by the Marine Corps. This plan specified that testing would be performed using several different minefield test arrays set up in various coastal environments. The test sites included a benign coastal environment at Eglin Air Force Base, a very cluttered coastal environment at Eglin, a cluttered grassy field also at Eglin, a moderately cluttered coastal environment at Marine Corps Base Camp Lejeune, and a homogenous grass field also at Camp Lejeune. These test sites were selected to be representative of a range of backgrounds from very easy to very difficult. For each background environment, several missions were flown under varying conditions including time-of-day, altitude, airspeed, type of minefield, and other conditions. In total, over 200 flight hours were flown during approximately 40 DT-0 test flights.

Two types of minefields were used during DT-0 testing: a staggered row patterned minefield and randomly scattered minefield. The former was used for the majority of test flights. The density and distributions of these minefields were chosen

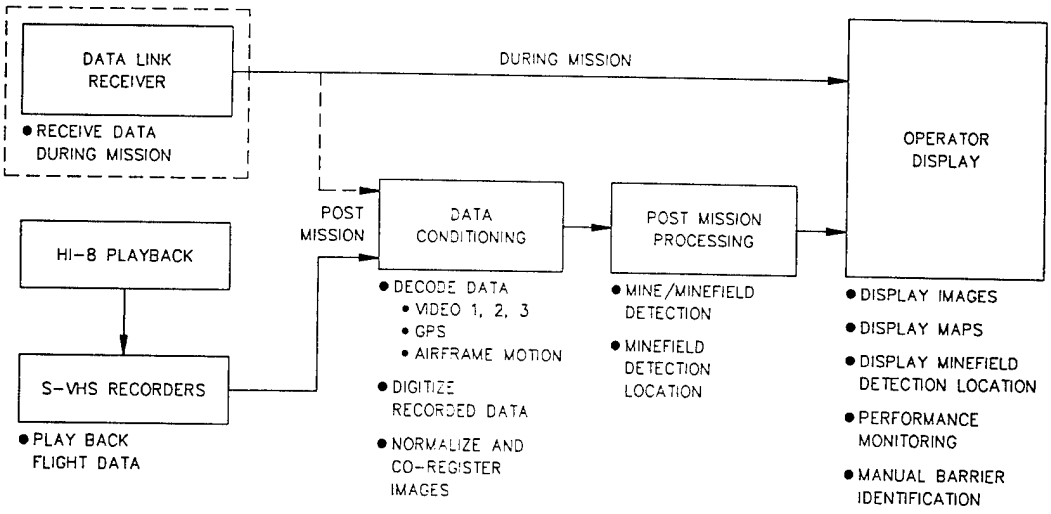


FIGURE 5. COBRA GROUND STATION SUBSYSTEM CONCEPT

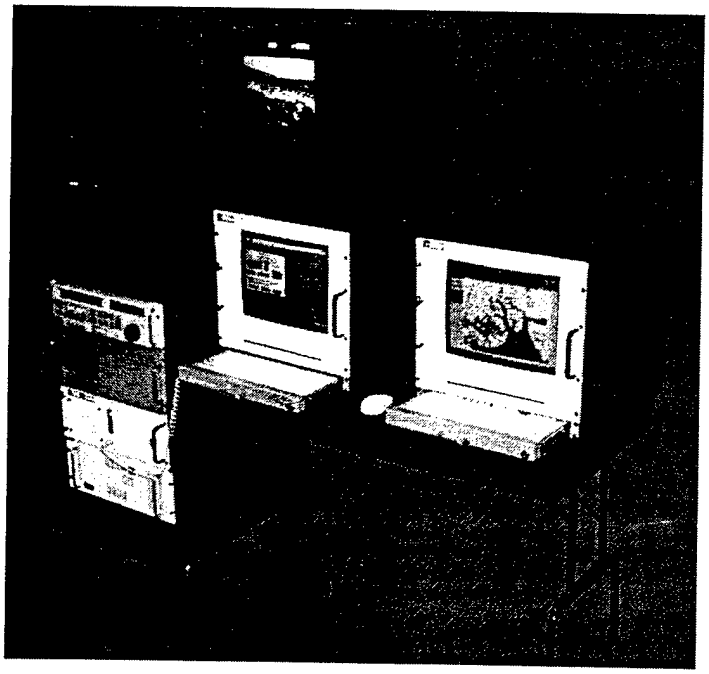


FIGURE 6. CTIDS GROUND STATION SUBSYSTEM

to be typical of deployed minefields. The COBRA sensors were flown over these minefields in a Cessna 172 aircraft acting as a surrogate to a Pioneer UAV. This afforded more flexibility and less cost in testing since the Pioneer is a fleet asset. The Cessna was flown at an altitude and airspeed corresponding to those used in our previous Pioneer testing[1] and for the current OT-0 testing in the Pioneer. The COBRA automatic minefield detection processing chain[2] was exercised on data from these flights to estimate a probability of detection versus probability of false alarm curve, called a Receiver Operating Characteristic (ROC) curve, for each type of environment. To estimate the ROC curves for each test condition, at least 25 minefield decision regions were collected and processed at each test field along with at least 25 non-minefield decision regions over the same test field. This provided a statistically significant number of samples from which to accurately estimate the ROC curves. After these 50 decision regions were collected and processed, the ROC curve was estimated by varying the threshold values for each minefield detection algorithm. Computing these values for a given threshold results in a single point on the ROC curve. Thus, varying the threshold from the minimum encountered value through the maximum value results in a complete ROC curve for each minefield detection algorithm.

The first test site analyzed was a benign coastal area at Eglin. This is a very clean beach with no significant environmental clutter. The beach is on the Gulf of Mexico with extremely white sand and typically relatively little wave activity. On the sand, the mines were clearly visible in all bands of the multispectral imagery and appeared as dark objects in an otherwise highly reflective scene. In the water, the mines were generally visible through the surf foam as well as at a depth of about 5-6 feet of water. In this type of non-cluttered environment one would expect highly successful minefield detection results. The ROC curve for this environment is presented in Figure 7 and shows both the patterned and scatterable algorithms have excellent performance. Selecting a typical operating point on the curve results in the patterned algorithm achieving Pd = 0.86 for a Pfa = 0.02 while the scattered algorithm achieves a Pd = 0.94 for a Pfa = 0.07.

The next test site analyzed was an extremely cluttered coastal area at Eglin. This test site presented many technical challenges. The water was stagnant and dark right up to the shore. The sandy region at the water's edge was only 1-2 feet wide. The water/land interface had areas which were rocky, as well as areas which contained metal trash, concrete, and other manmade debris. The inland area of this test region was no less cluttered. There were areas of patchy grass, trees 10-20 feet high, small scrub bushes and a couple of areas with just benign sand. The inland areas changed background characteristics very rapidly, highlighting the need for localized measurement of background statistics for the mine detection algorithm to be successful. Also, because of the very diverse backgrounds, the need for a variety of spectral bands was apparent since the optimal bands for mine detection are different for each type of background and there may be two to three very different backgrounds appearing in each multispectral image. Typical performance results from this test site showed that the patterned algorithm successfully passed the detection and false alarm goals, but just barely. The scattered algorithm, however, was even more successful.

A variety of other test cases were processed from the DT-0 data[6], including processing a 40 second long pass covering a minefield and many different background environments occurring along the aircraft's track. A preliminary pass of OT-0 data which is over a minute-and-a-half long has also been processed. In all cases, the COBRA system is meeting or exceeding the ATD goals for the program.

5.0 ACKNOWLEDGMENTS

The Coastal Systems Station, Naval Surface Warfare Center-Dahlgren Division serves as the Technical Direction Agent for COBRA. ERIM is the prime contractor for the program. Mr. Ned Witherspoon is the Project Engineer and Mr. Bob Muise is the Image Processing Lead for the program. Dr. Jim Wright is the lead engineer for the ground station development. The program sponsor is Mr. David Vaughn, Director, Amphibious Warfare Technology, Marine Corps Systems Command.

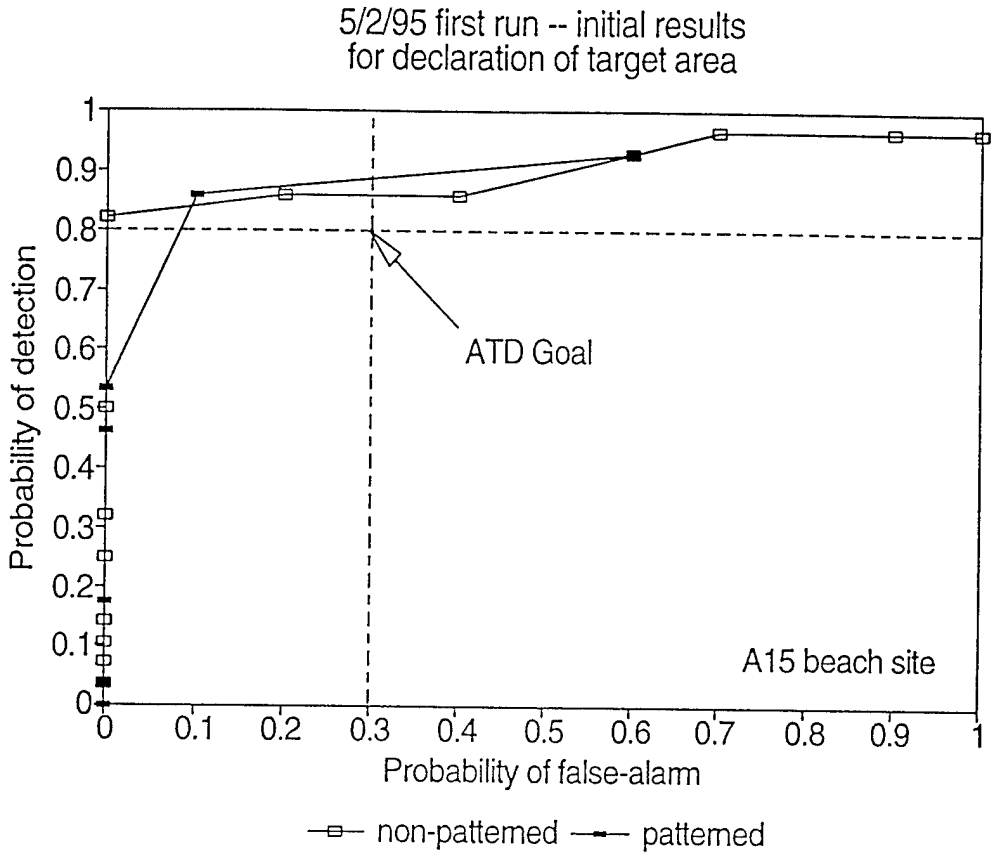


FIGURE 7. ROC CURVE FOR BENIGN COASTAL ENVIRONMENT

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Clandestine Mine Reconnaissance - Unmanned Undersea Vehicles

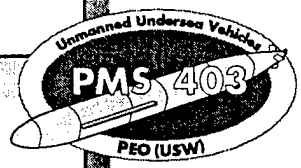
CAPT Charlie B. Young, USN
Program Manager,
U.S. Navy Unmanned Undersea Vehicles
Program Management Office

21 November 1996

Clandestine Mine Reconnaissance Unmanned Undersea Vehicles

Presented to: Technology & the Mine Problem Symposium

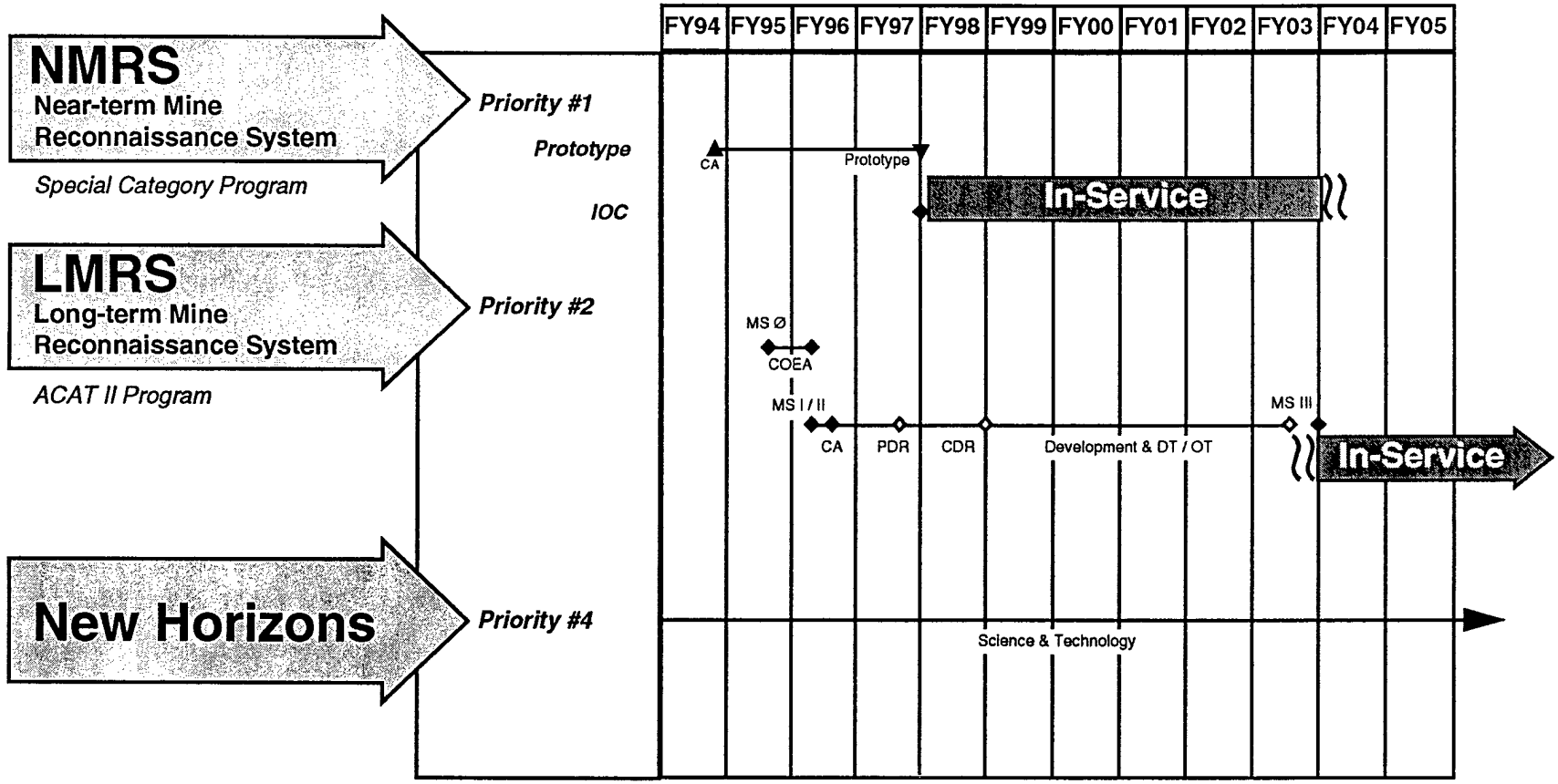
Presented by: CAPT Charlie B. Young, USN



Purpose

- **Provide overview of Navy UUV programs**
- **Operational concepts for UUV in role of "clandestine mine reconnaissance"**
- **Overview of UUV technology development**

Navy UUV Program Plan

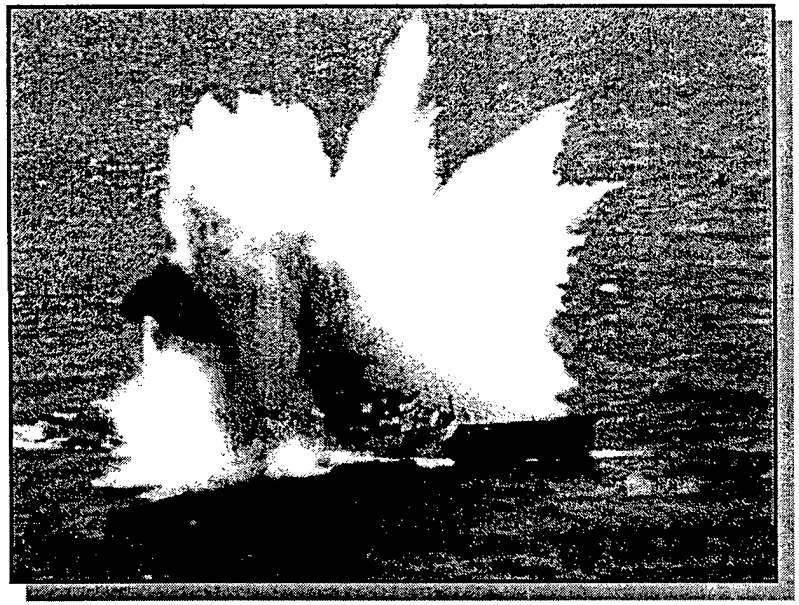


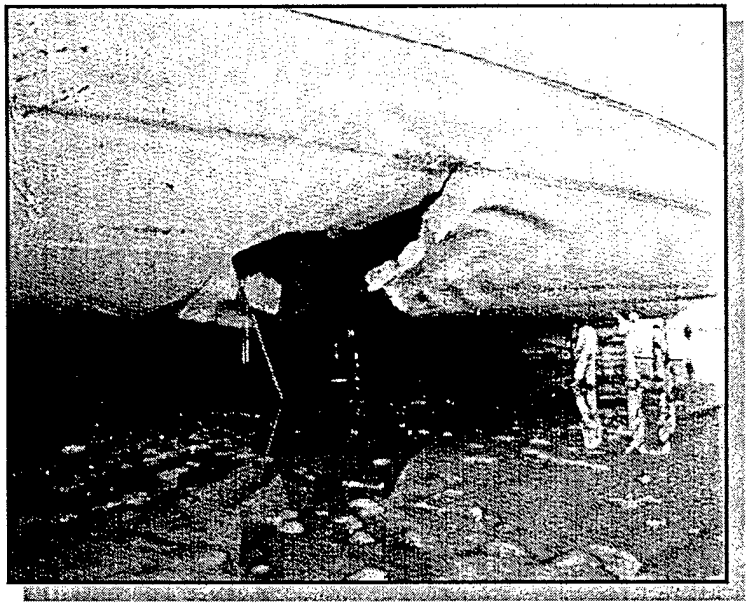
Both programs are on track

Mine Warfare Need

"Within the area of mine warfare, the most significant shortfall is the early and sustained knowledge of where and when an enemy has deployed its mines."

Maj. Gen. H. Jenkins, N85, Feb 94

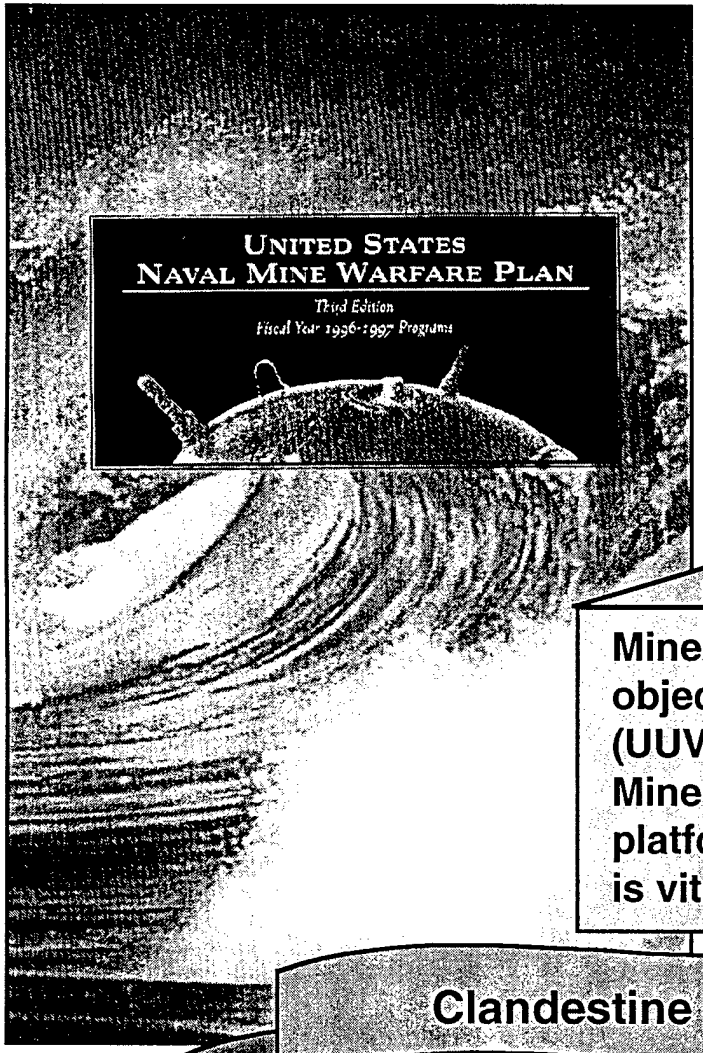




Development of a clandestine mine reconnaissance capability is the Navy's top mine warfare priority

MIW Plan, 2nd Ed.

Mine Warfare Plan



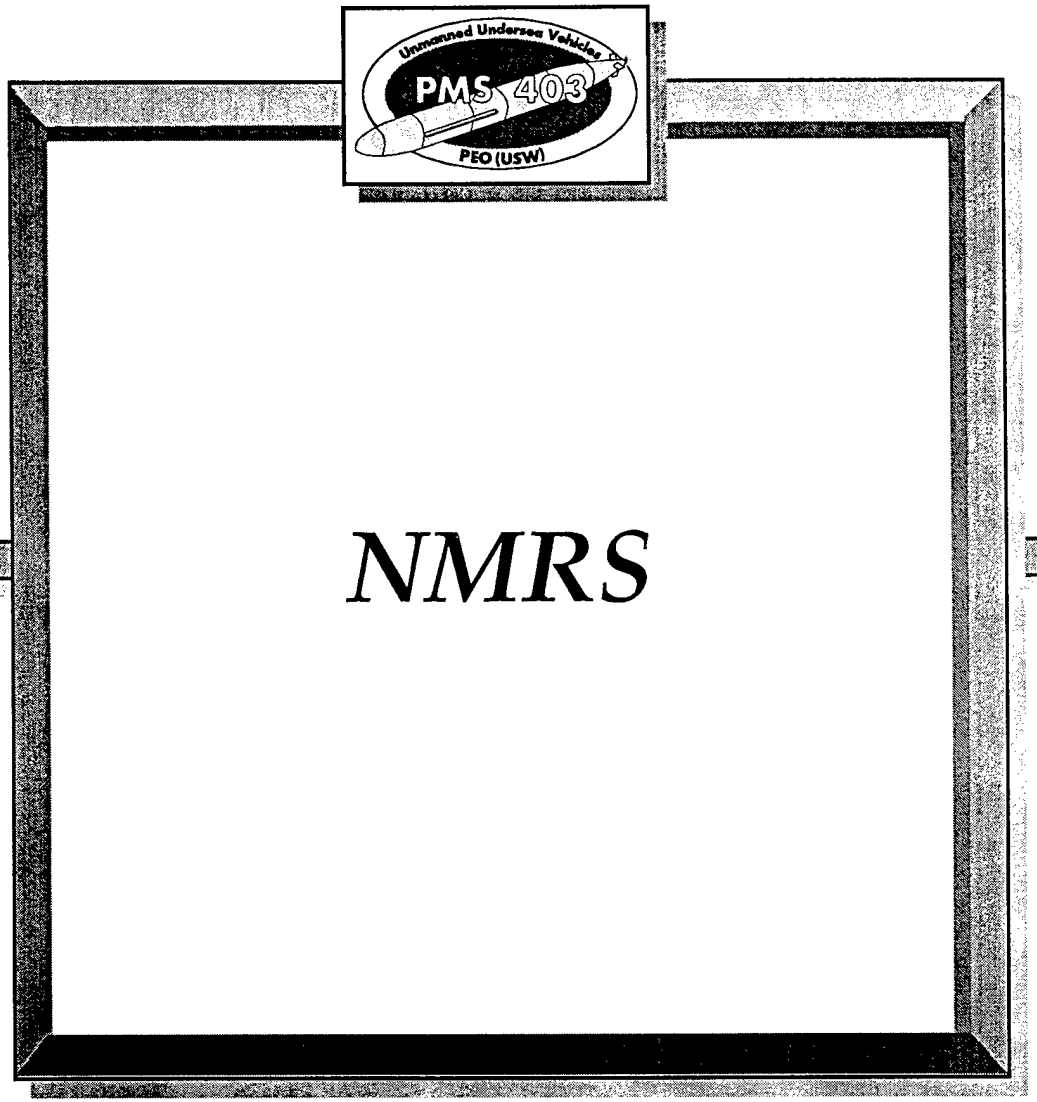
water to a portion of the VSW region. The RMS program acquisition strategy calls for a streamlined approach, delivering contingency capabilities to the Fleet near term, enroute to the final, fully supported RMS system. Completed in August 1994, the Remote Minehunting Operational Prototype (RMOP) represents the first contingency system capability. As a non-developmental initiative within the RMS program, RMOP combines and integrates the AN/AQS-14 minehunting sonar (on a variable depth winch) and the SEABAT forward looking sonar with the DOLPHIN semi-submersible. Additional follow-on developmental contingencies are being advanced to meet mid-term requirements, including improved vehicle performance and integration in *Spruance* (DD 963) class destroyers.

Near-Term Mine Reconnaissance System (NMRS)

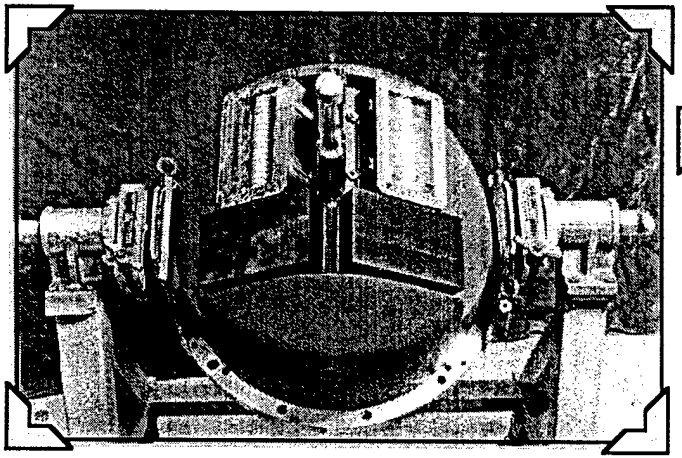
Mine reconnaissance is the Navy's highest mine warfare objective as well as the top Unmanned Undersea Vehicle (UUV) priority. Knowledge of the full dimension of the mine threat without exposing the reconnaissance platforms and the intentions of the tactical commander is vital to littoral warfare. To this end, both near-term and long-term programs have been established to deliver UUV mine reconnaissance

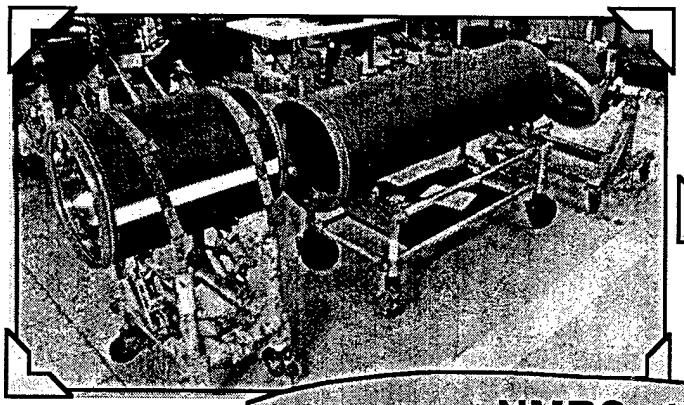
Mine reconnaissance is the Navy's highest mine warfare objective as well as the top Unmanned Undersea Vehicle (UUV) priority. Knowledge of the full dimension of the Mine threat without exposing the reconnaissance platforms and the intentions of the tactical commander is vital to littoral warfare.

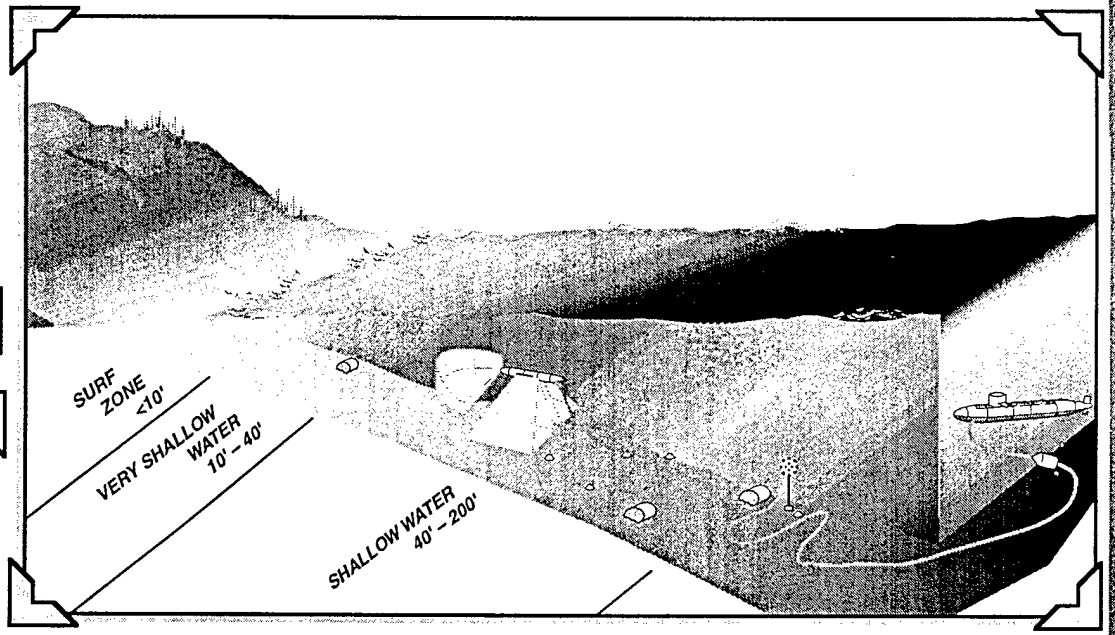
Clandestine Mine Reconnaissance


Unmanned Undersea Vehicles
PMS 403
PEO (USW)
NMRS

Near-term Mine Reconnaissance System



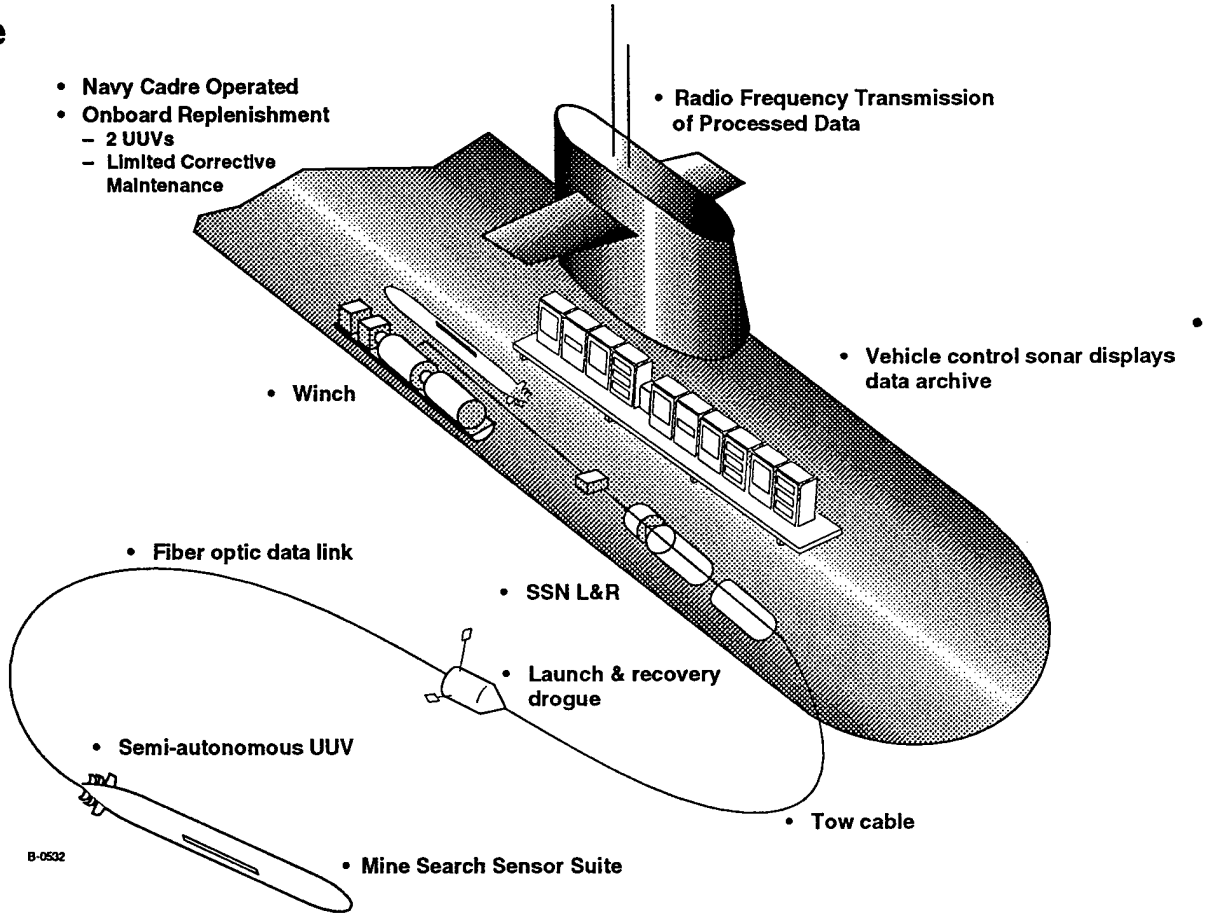




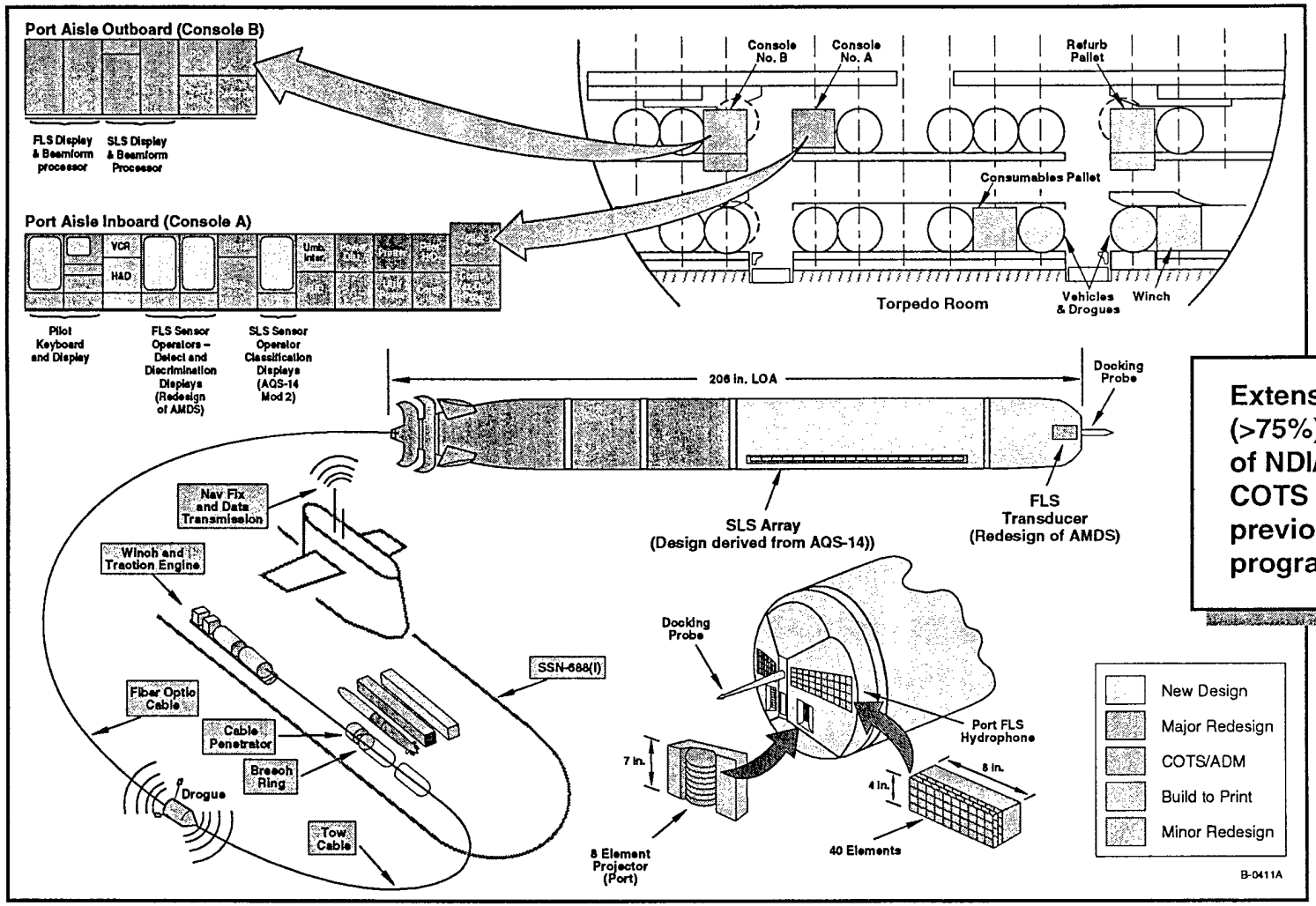
NMRS stop-gap, interim operational prototype capability

NMRS Concept of Operations
Deployment Concept

- **All NMRS equipment to be located in SSN Torpedo Room**
  - Standard weapons loadout for SSN is reduced
- **Operator controlled system during reconnaissance mission**
- **Re-supply / refurbishment**
  - Return to in-theater site
  - Return to CONUS



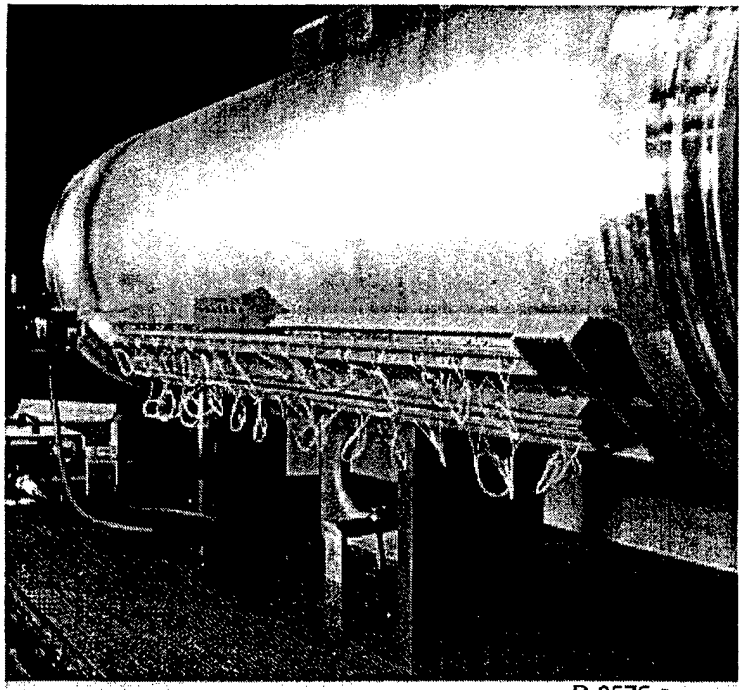
NMRS System Architecture



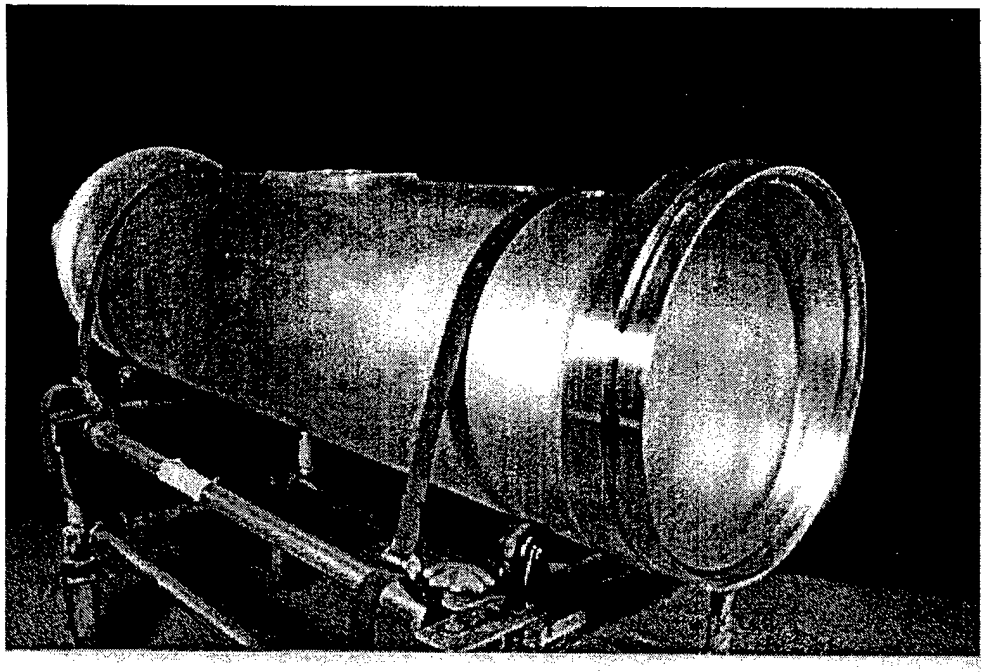
Extensive (>75%) use of NDI/ COTS from previous programs

Unmanned Undersea Vehicles (UUVs)

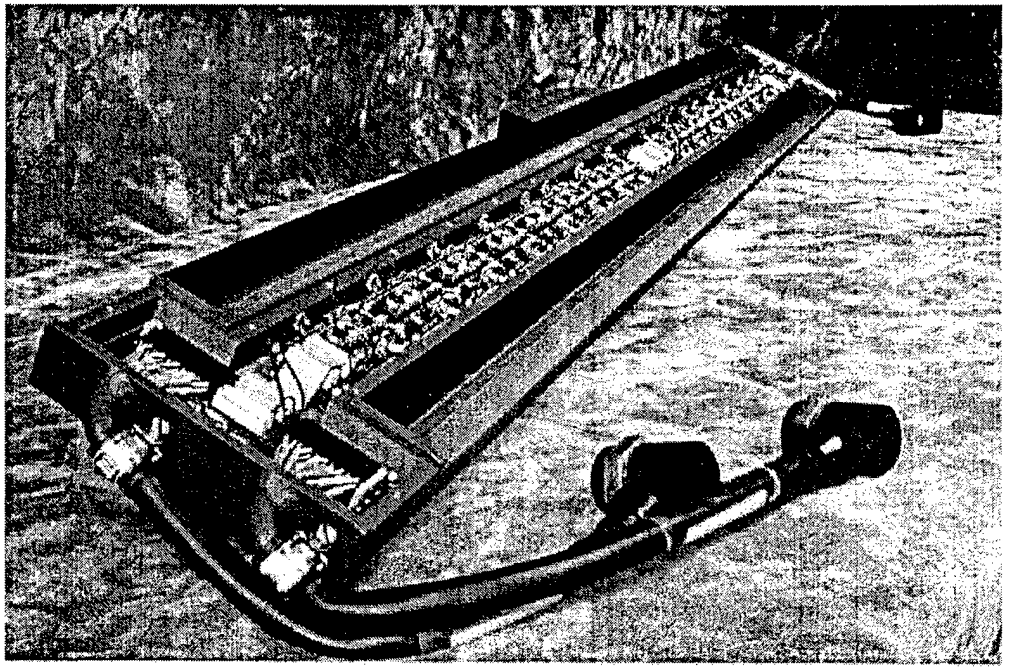
- **UUV characteristics**
  - 21" dia., 206" length, approx 2250 lbs.
- **Sensors**
  - Forward Looking Sonar (FLS)
    - Detection and classification of Volume Mine-Like Objects (MLOs)
  - Side Looking Sonar (SLS)
    - Classification of Bottom MLOs
  - Homing and docking sonar
    - UUV rendezvous & recovery
- **Zn-AgO battery provides energy source**
  - SSN provides power for UUV hotel loads prior to UUV separation and during recovery
- **Communication with SSN via the Fiber Optic Data Link (FODL)**
  - UUV transits autonomously to preprogrammed rendezvous point if FODL breaks



B-0575 s

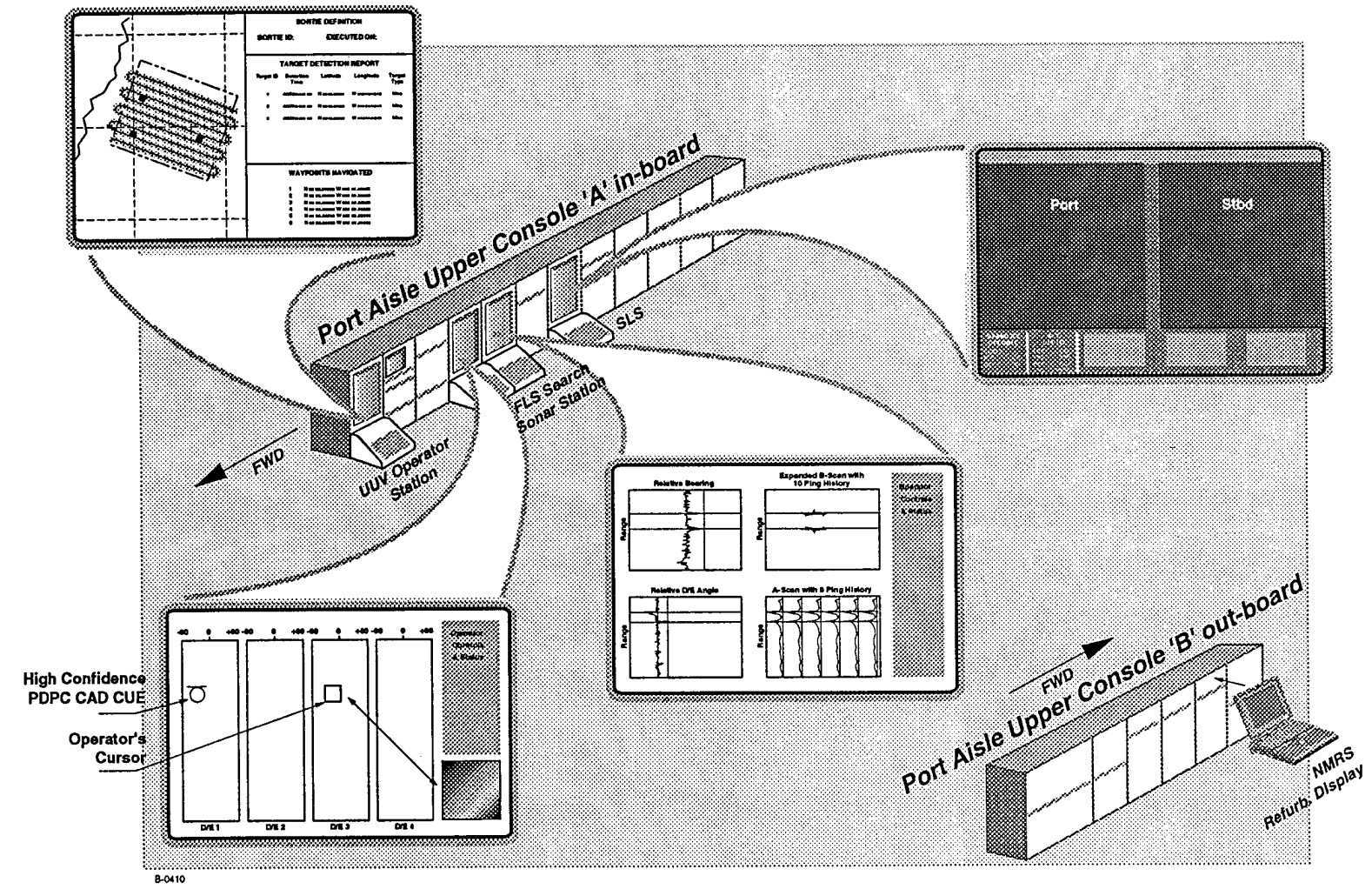


B-0576 s



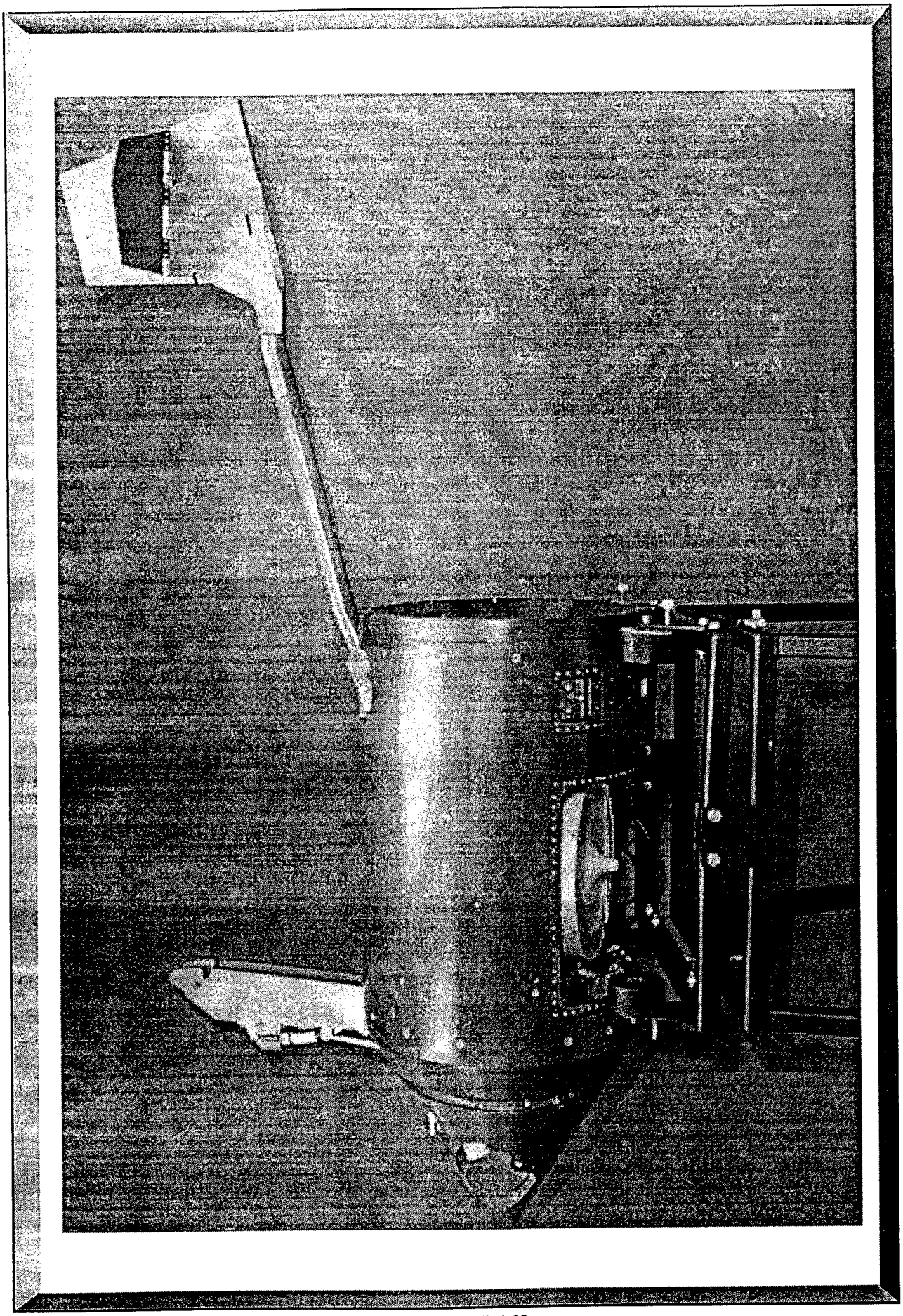
B-0577-S

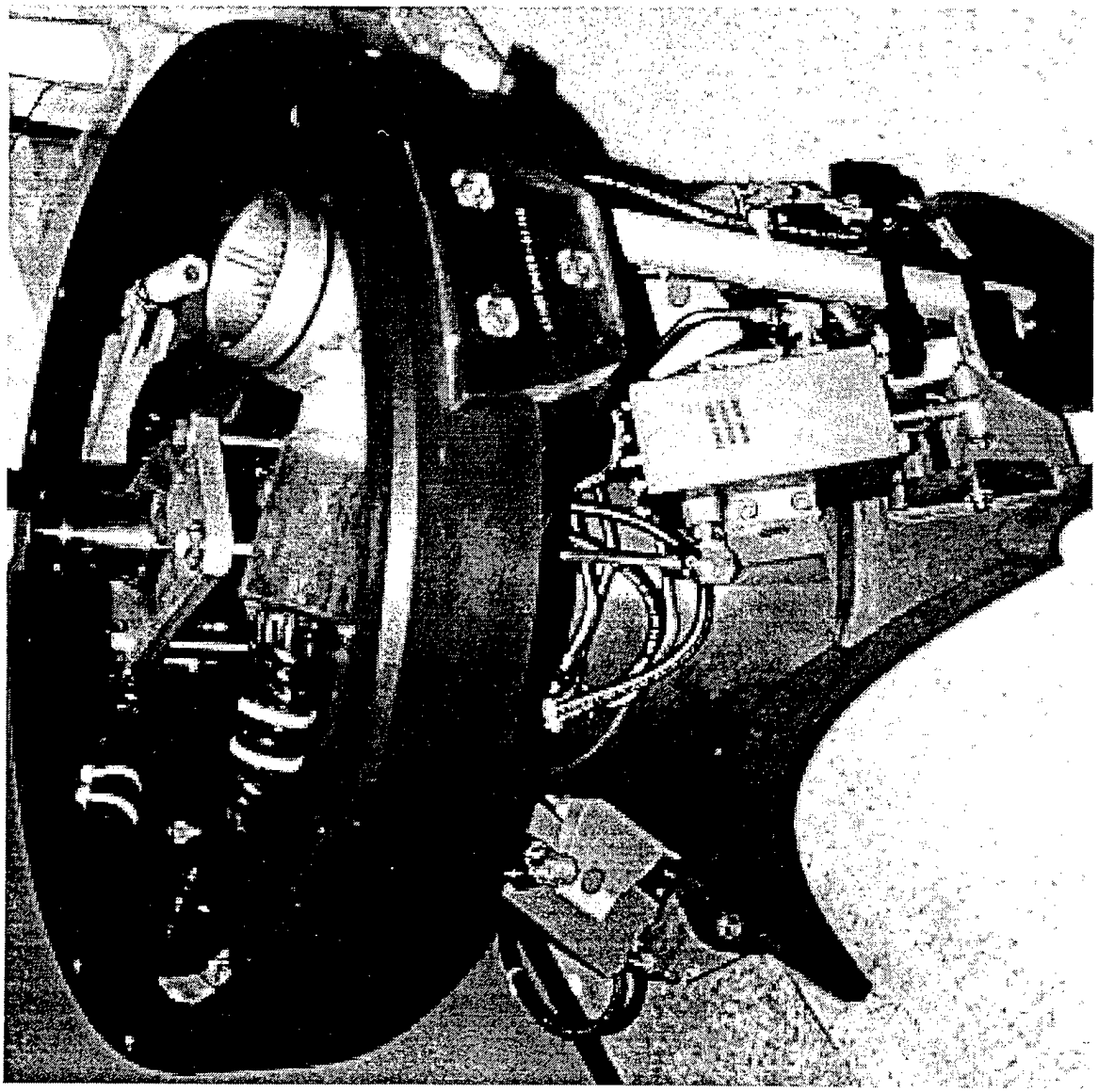
Control and Display Consoles

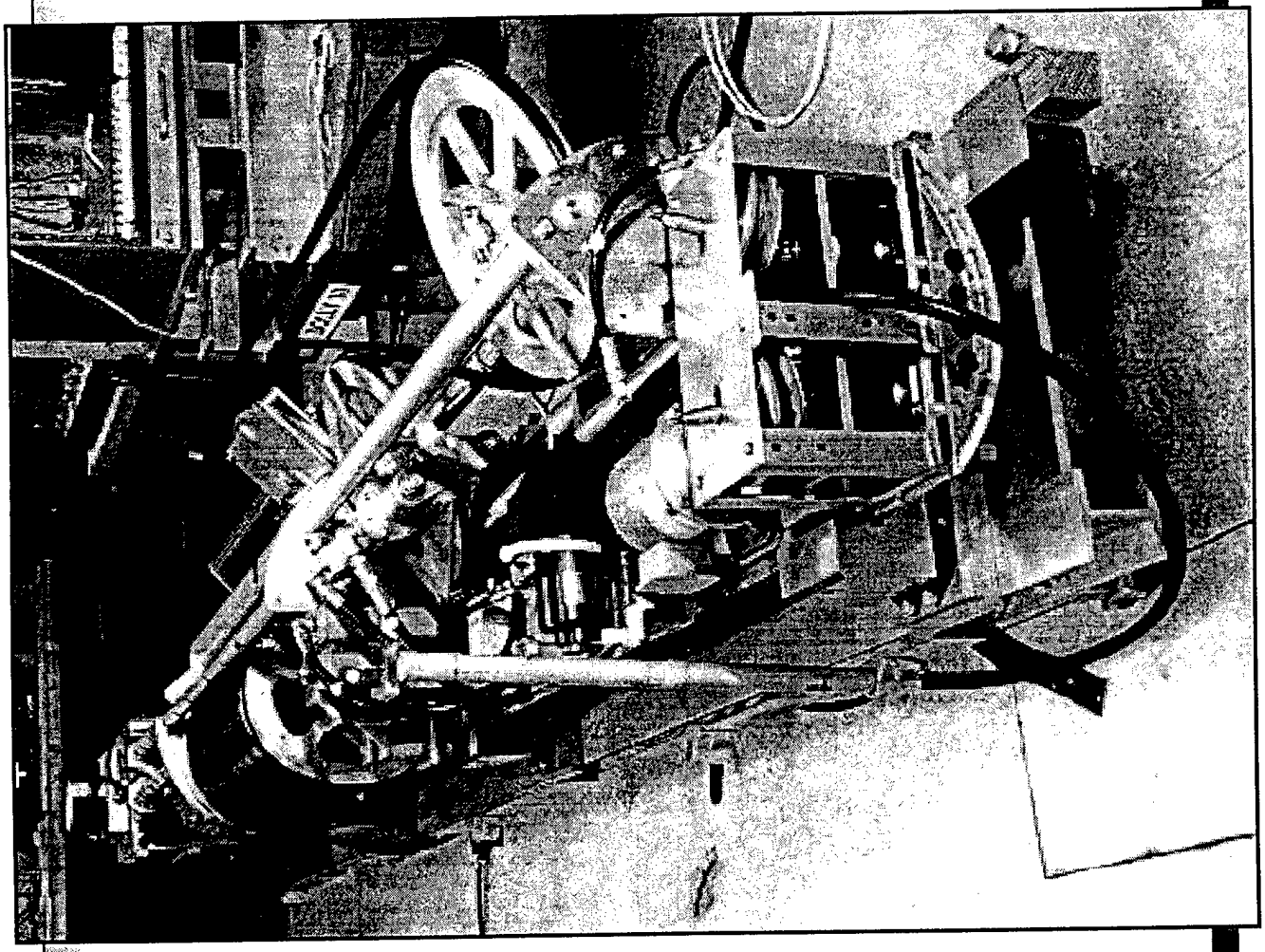


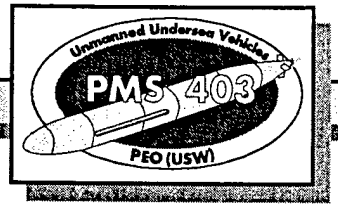
Launch and Recovery (L&R) Equipment

- **Torpedo tube**
  - Modifications to breech door for electrical, hydraulic and tow cable interfaces
  - Breech ring stabilizes UUV / drogue combination in tube
- **Drogue**
  - Stabilizes UUV when in tow configuration
  - Deploys FODL to maintain low fiber tension
  - Contains homing and docking sensors for UUV recovery
- **Winch and traction engine**
  - Aids launch by "pushing" tow cable through breech door seal
  - Used for pulling UUV/drogue into torpedo tube during recovery operations



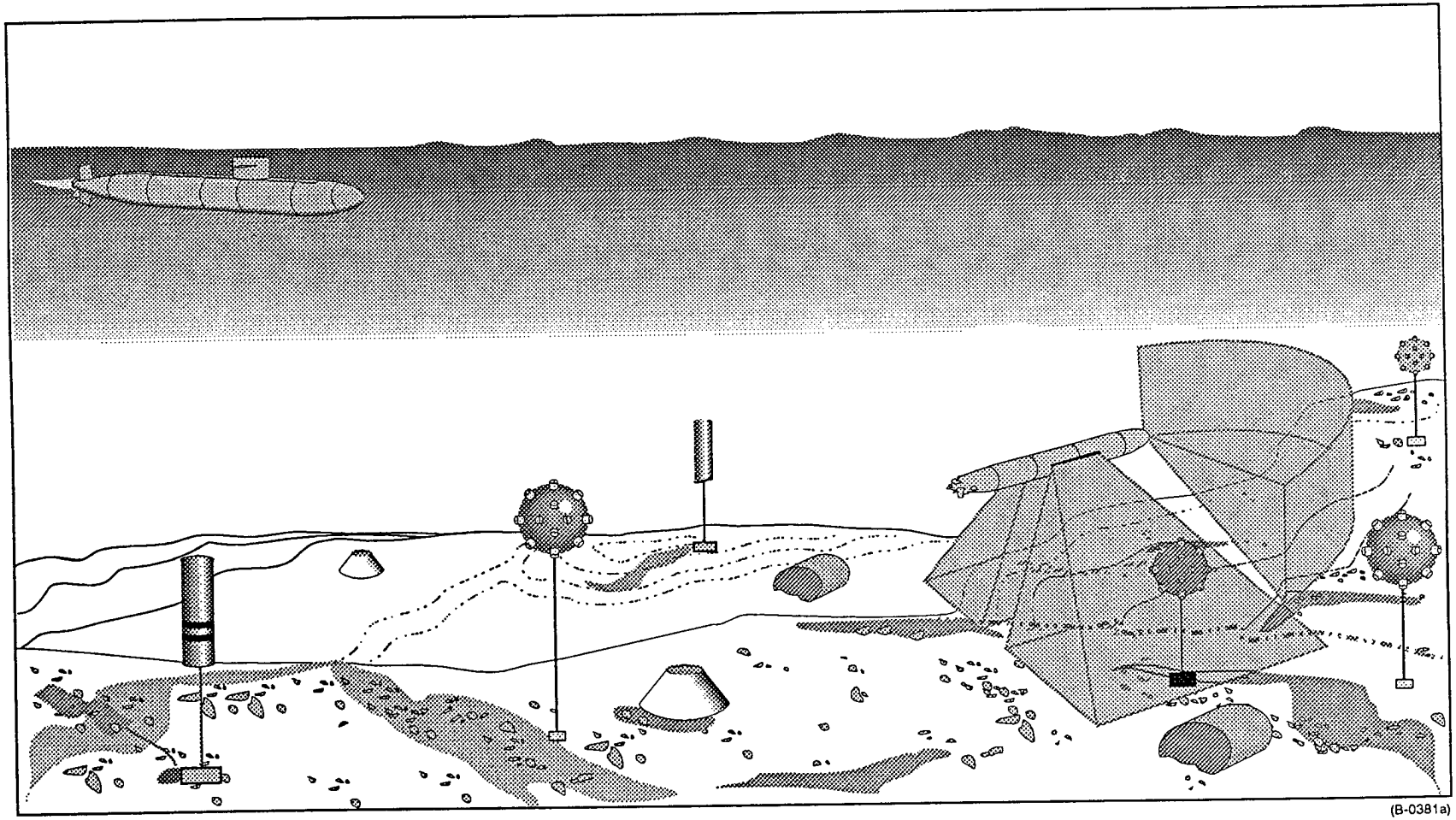






LMRS

Long Term Mine Reconnaissance System



LMRS Performance Specification



Torpedo Tube L&R

2 Autonomous UUVs

RF and/or Acoustic Comms

GPS Position Fix Capability

Advanced Forward-look Search Sonar

Advanced Energy Source (4 to 5X Zn-AgO) Moderate Risk: Replaceable

Side-Look Classification Sonar

Single Sortie Reach	~	75	– 120	nm
* Total Area Coverage	~	400	– 650	nm²
Area Coverage Rate	~	35	– 50	nm²/day

UUV Reliability Improvements : ~ 5-8 x over NMRS
Reliability Cost Growth ** : ~ 15% in Development
: ~ 20% in Production

Cost (Constant FY95 M$'s):				
Development:	88	131	(1 system)	Procure 6–12 Systems
Production:	91	100	(6 systems)	
O&S:	110	153	(6 systems 20 yrs.)	
LCC	289	384		

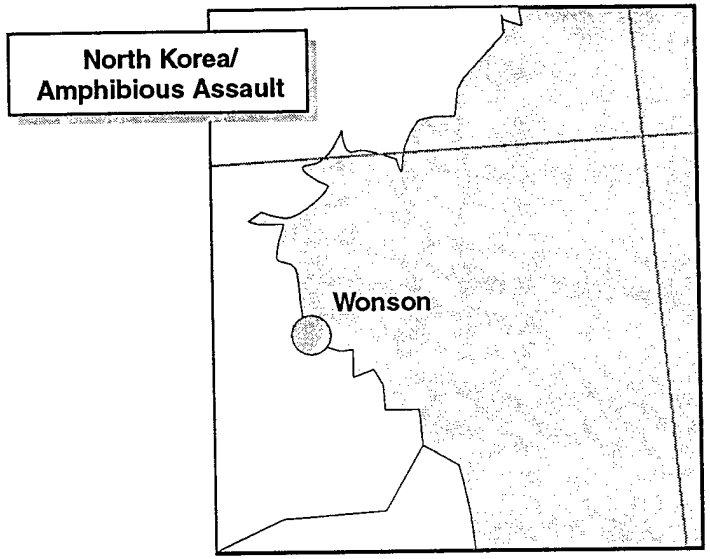
* TAC estimates assume 2 replaceable energy sections

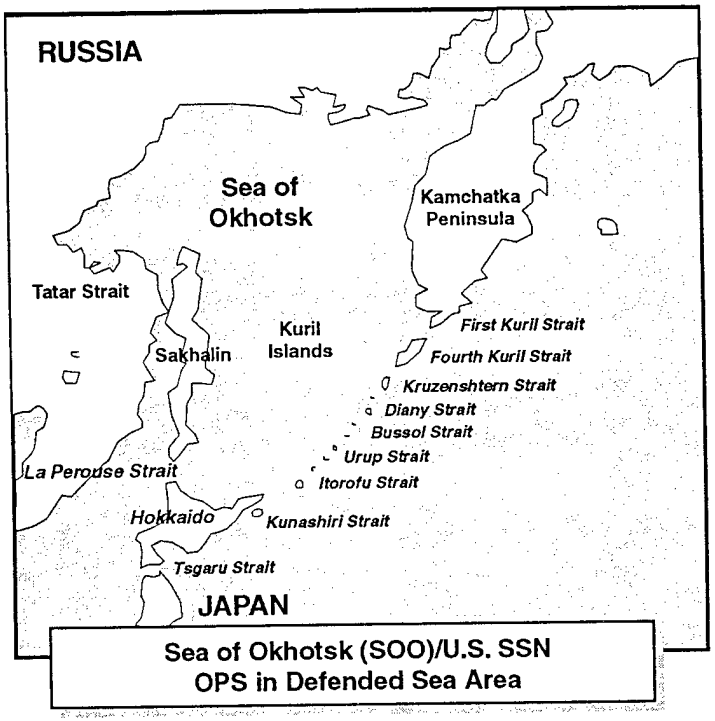
** Percent increase in Total Program Cost Estimate for Indicated phase

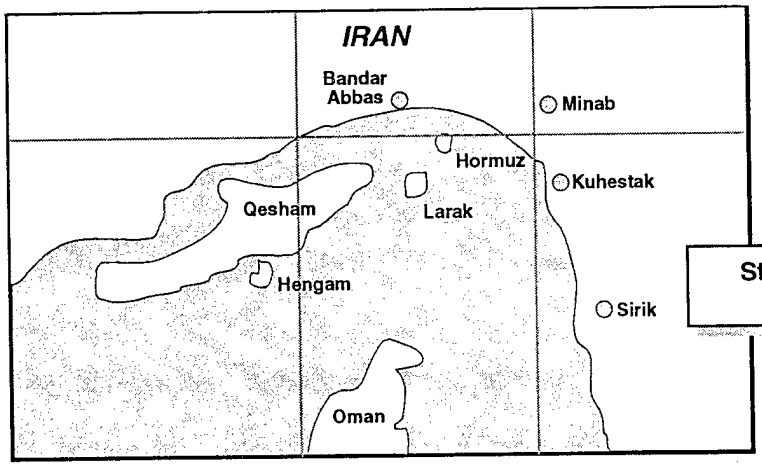
Low Medium High

B-0546

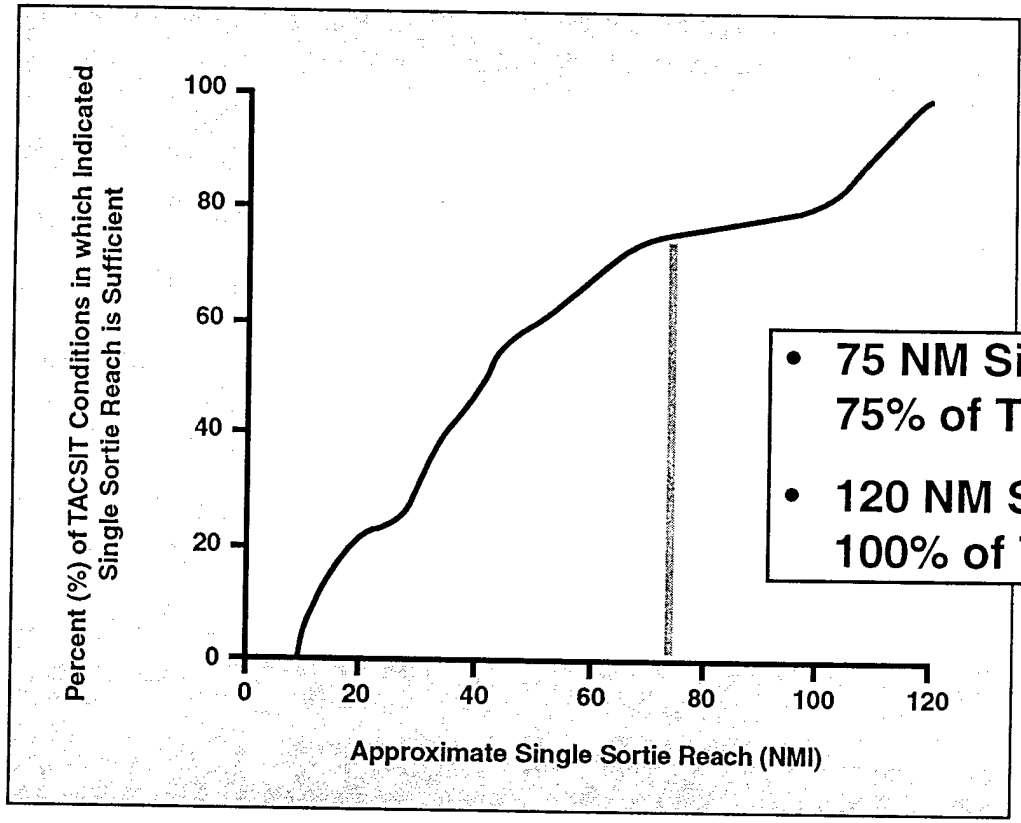
Scenarios and TACSITs for LMRS COEA







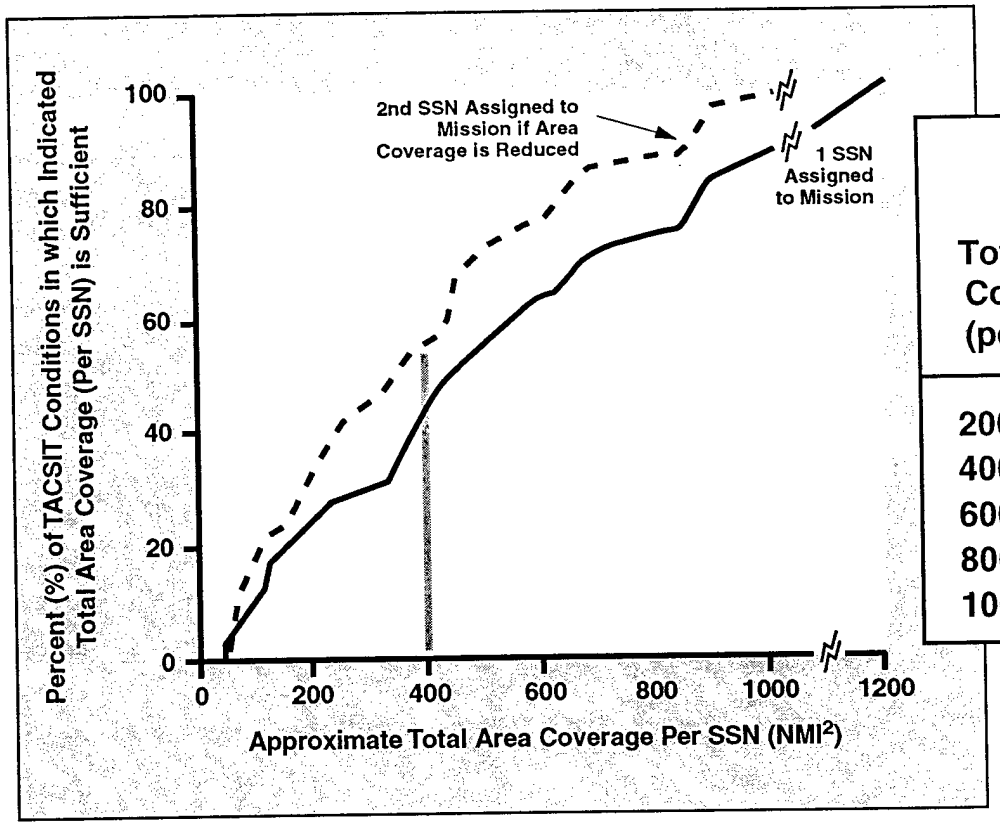
Adequacy of Single Sortie Reach Capabilities for Various TACSIT Conditions



- 75 NM Single Sortie Reach covers 75% of TACSIT conditions
- 120 NM Single Sortie Reach covers 100% of TACSIT conditions

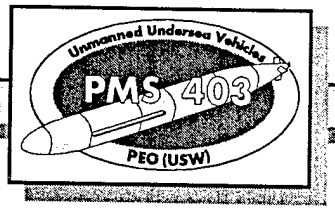
B-0591 L

Adequacy of Total Area Coverage Capabilities (per SSN) for Various TACSIT Conditions



B-0591 R

Total Area Coverage (per SSN)	≈ % of TACSIT conditons in which indicated total area coverage (per SSN) is sufficient	
	Only 1 SSN Assigned	2nd SSN Assigned if Beneficial
200 NMI1	25	35
400 NMI2	45	55
600 NMI2	65	75
800 NMI2	75	88
1000 NMI2	88	98

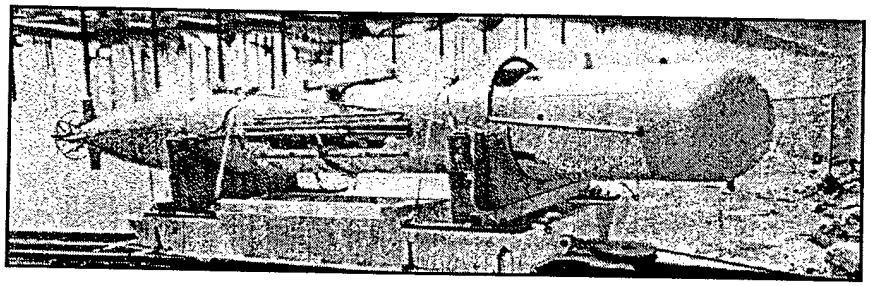


UUV Technologies

Applicable Science and Technology Efforts

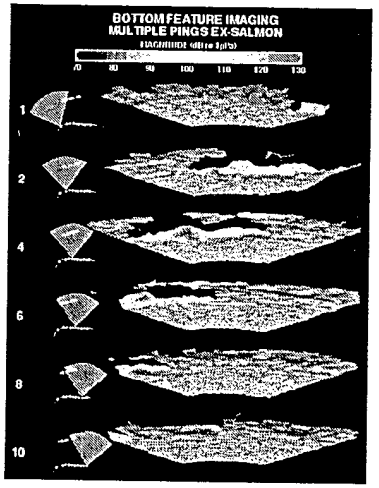
- **Driven by UUV needs and risk areas**
  - Sonar
  - Energy
  - Autonomy
- **Activities**
  - Sonar
    - AMMT
    - HRA
  - Energy
    - Lithium battery
    - Thermal engines
    - Semi-fuel cell
  - ONR UUV techbase

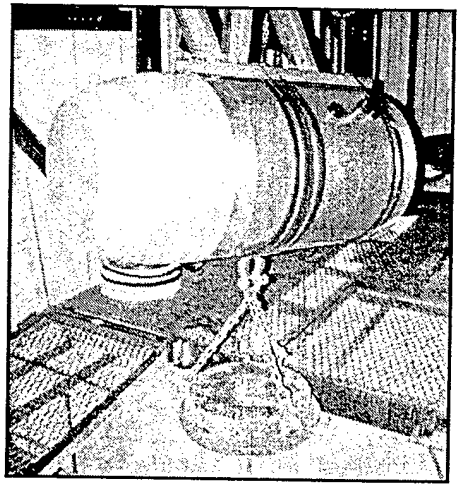
Sonar and Autonomy Related Efforts



Advanced Minehunting and Mapping Technologies (AMMT)

- **AMMT program and the Mine Search System (MSS) program demonstrated the feasibility of an autonomous mine hunting UUV**
- **44" diameter, 40' long UUV, displacing 21,000 lb.**
- **Forward look search sonar, with**
  - Classification sonar (MSS)
  - Laser Line Scan and Camera (AMMT)

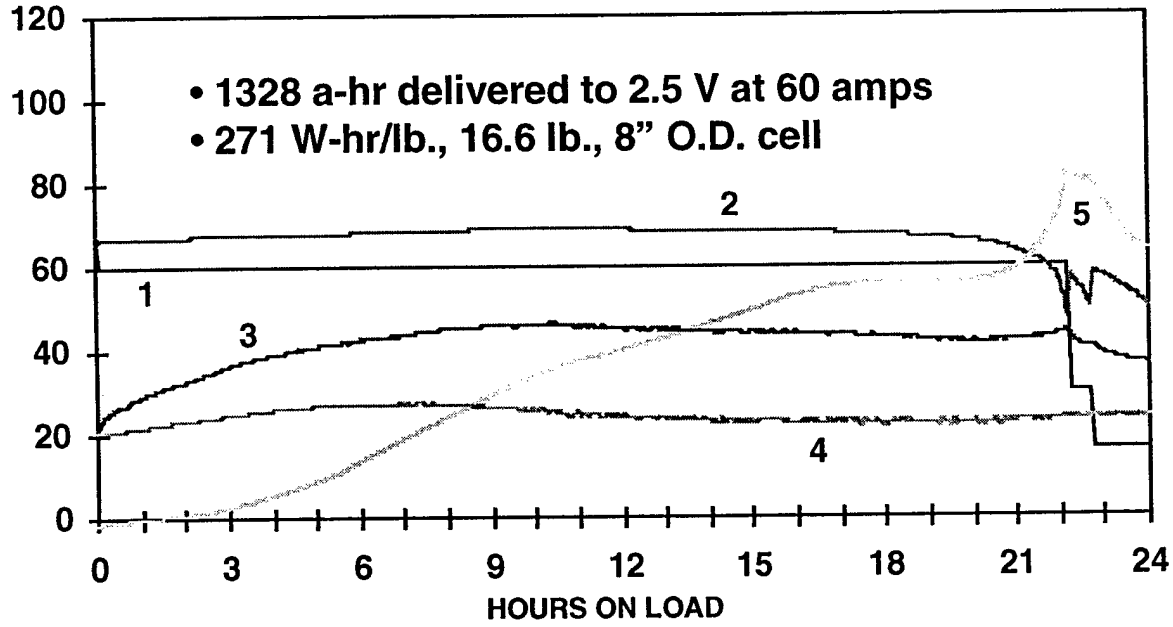




High Resolution Array (HRA)

- **Very high performance 21" UUV sonar**
  - Originally designed for shallow water torpedo G&C ATD
  - Subsequently adapted for transition to MCM UUV
  - 87 kHz, 3 deg. beams, 10% bandwidth
    - 1272 1-3 composite elements

Energy Related Efforts: Li-SOCl2 Battery



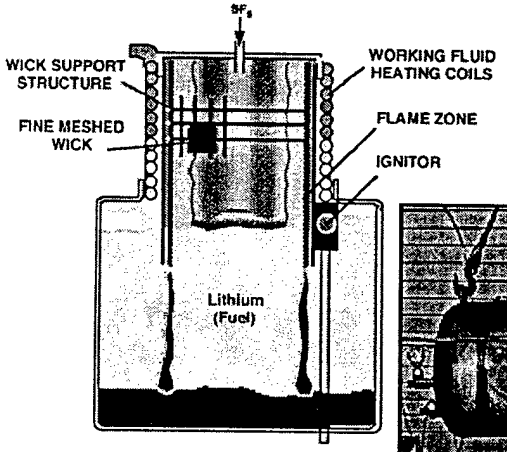
Series1
Series2
Series3
Series4
Series5

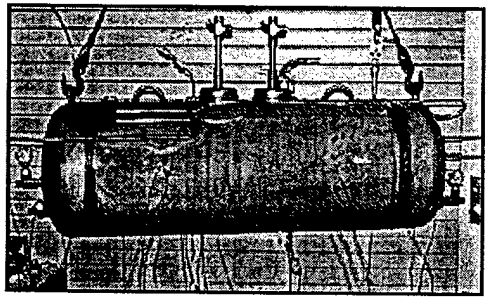
Series 1: Cell current (60 amps)
Series 2 is cell voltage times 20 (average 3.38 V)
Series 3 is cell surface temperature (average 41.7 C)
Series 4 is ambient temperature (average 24.1 C)
Series 5 is cell internal pressure (max. 82.5 psig)

- Developed a higher rate version of the Li-SOCl2 battery to support UUV rates (up to 10 W/lb.) in a Phase 1 SBIR; over 6x Zn-AgO Energy Density
- Phase 2 SBIR efforts now underway to develop a 1/3 scale UUV battery and conduct safety testing

Energy Related Efforts (continued)

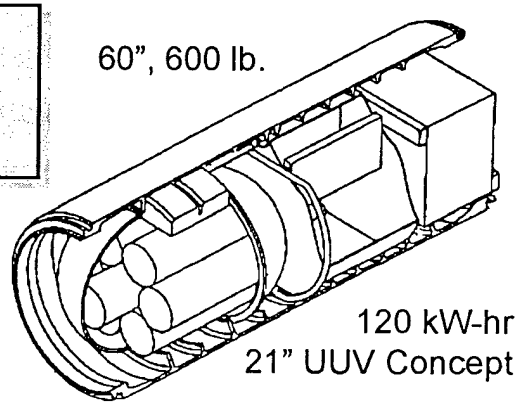
Lithium-SF6 Wick Combustor





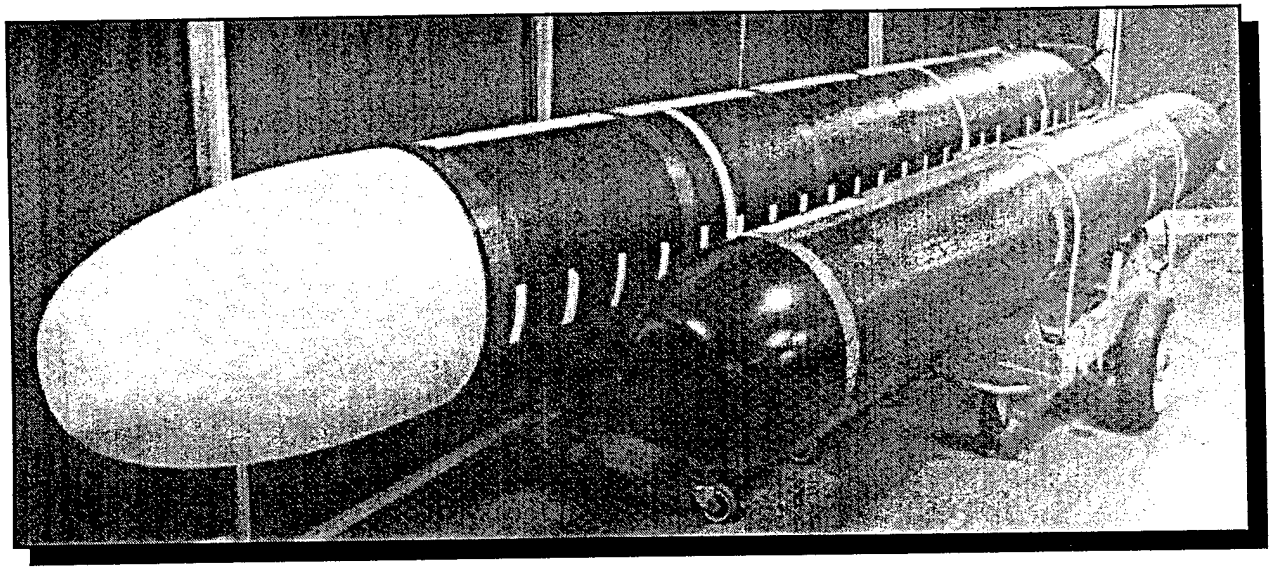
- **Thermal engine efforts focus on the ARL/PSU molten lithium - sulfur hexafluoride "wick" combustor with either Rankine or Stirling energy conversion with alternator and buffer battery**
  - Highest energy yield of potential UUV energy sources
    - 5 to 8x Zn-AgO
- **Photo is of a 100 hour endurance fuel tank with two combustors installed**

Aluminum Semi-Fuel Cell Efforts



- **DARPA efforts have just concluded**
  - Aluminum-Oxygen (air cathode)
  - Oxygen is generated from the decomposition of Sodium Chlorate Candles (NaClO3)
  - Energy yield is 3 to 4 times Zn-AgO
- **NUWC/ONR approach employs the direct reaction of a liquid catholyte (e.g. H2O2, NaClO) on an electrocatylitic surface in a bipolar cell stack**
  - Fewer moving parts
  - Increased reliability
  - Increased energy yield (4-5x Zn-AgO)

UUV Technologies



- Non-traditional navigation
- Low speed control
- Acoustic Quieting
- EM Quieting
- Autonomous processing
- Fault monitoring and isolation
- Novel structures
- Advanced Propulsors
- Advanced Motors

- **The balance of the UUV technologies are developed under the ONR UUV Technology program and tested on one of two NUWC UUV test beds**
  - LDUUV: existing 26.5" diameter x 282" testbed
  - 21UUV: 21" diameter x 244" testbed (FY97 IOC)

Summary

- **US UUV efforts are focused by the UUV Program Plan priorities:**
  1) Stop gap mine reconnaissance capability by FY98
  2) Greatly improved capability to replace the stop gap system
  3) Surveillance/Intelligence collection
  4) R&D to support future missions
- **NMRS is on schedule will be fielded in FY98**
  - One system with two UUVs
- **LMRS contracts have just been awarded**
  - Order of magnitude capability improvement, IOC 2003
- **Strong R&D efforts exist in critical areas**
  - Energy
  - Sonar

The Iguana:
A Mobile Substitute for Landmines

Prof. John Arquilla
and
Barbara Honegger, M. S.
Naval Postgraduate School

As President Clinton, Secretary of Defense William Perry and the international community were sending out a call in May 1995 for a worldwide ban on anti-personnel landmines by the turn of the century, a unique solution to that very problem was being readied for an initial test.

The problem is immense and well known. Each year worldwide, the 100 million or more landmines currently in place kill or maim over 20,000 innocent civilians, including children; and, despite demining efforts, a net addition of 500,000 accrues each year. Even relatively "new" solutions to the problem, like using only "smart" or self-destructing mines, leave deadly buried bombs in the sand and soil for a set period of time. And a worldwide ban leaves the critical military problem of how our forces and allies can secure territory if landmines aren't to be used at all.

Our solution, called "Brilliant Minefields," is a teleoperated, weapons-mobile ground combat system designed to avoid the need to use landmines. For military operations, it would replace them with fast, flexible all-terrain vehicles equipped with monitoring devices and rocket-propelled explosives capable of taking out tanks, light infantry, aircraft and, perhaps eventually, even missiles. Human operators would scan video screens miles from the battlefield, firing remotely at their targets.

Because this new, high-mobility, low-profile weapons platform is amphibious (able to move easily both on land and in water) and self-righting (able to "get back on its feet" if it falls over), we named it the "Iguana."

Iguana is small and fast -- six feet wide, 15 feet long and about waist high, with an average tank-compatible speed of 30 to 45 miles per hour, and future speeds of up to 60 mph. It was designed for amphibious assaults -- to be able to go in with the Marines in front of, at the side of, or behind expeditionary forces, to provide flank security for troops as a key element of future littoral, or near-shore, conflicts.

The Iguana makes both strategic and humanitarian sense. It will enable our forces and those of our allies to secure territory while reducing the cost of fighting, increase the range and coverage of targets, eliminate the need for secrecy of placement, and reduce to zero the number of new mines that can cause collateral, or unintended, damage. It would have been an ideal response, for instance, to the 1990 Iraqi invasion of Kuwait -- or to a similar future intrusion.

In the summer of 1996, the Naval Postgraduate School and Naval Research Laboratory performed a manned test of the first prototype developed in Oregon. NRL funded the vehicle engineering and control system studies, and NPS was responsible for field systems analysis. The NPS Iguana team consists of Prof. John Arquilla, Prof. Mike Melich and Prof. Pat Parker.

Although the system will eventually need to be integrated with air cover and other defenses, it would not necessarily require U.S. control and operation, and might be purchased and operated solely by allies, such as Kuwait. In fact, should current restrictions on the use of robotic weapons on the battlefield be further eased, the first place the vehicle could be used in actual operations might be in Kuwait, as early as the fall of 1998.

The Iguana and the "Brilliant Minefields" concept are tangible results of the new cyber- or information-warfare thinking. Because it's unmanned and operated from a distance, relying heavily on teleoperations, the vehicles need timely and accurate information to be effective.

Such teleoperated ground combat systems will become an absolute requirement in a world in which landmines have been banned.

Mission definition for AUVs dedicated for war gas ammunition deposit assessment

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Faculty of Ocean Engineering
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Summary:

There are a number of sites where WWII war gas deposits have been placed on the sea bottom. In the Baltic Sea, there are two such areas -- one situated east of Bornholm and the second west of Gotland -- together containing 35,000 to 50,000 tons of WWII war gas ammunition of various types [1], [2]. Due to a number of reasons, there has been no systematic evaluation of the condition of or any regular monitoring of these deposits. One of the main obstacles to long-term monitoring of environmental impacts of war gas deposits is their unknown three-dimensionl distribution in the sea bed. Another major obstacle to setting assesment procedures is the cost of information gathering. Although the utilization of surface vessels is very costly, it can bring detailed results and such application is justified in a large-scale projects given sufficient financial support.

Development of new technologies for ocean floor documentation, particularly AUVs and their work packages, creates new possibilities for cost-effective reconnaissance of targeted areas which are known locations of war gas deposits. Application of precise surface and underwater navigation allows for periodical survey of selected sites. New search and classification tools available on the commercial market can produce more data of better quality. The safest way of cost-effective information gathering is through the application of robotic systems for step-by-step data collection. Following a survey of selected points, areas for more detailed investigation can be selected. The type of information required includes target mesh coordinates, ammunition type, corrosion status, and danger status, and can be obtained from data collected by dedicated AUVs performing search and data collection missions.

Background of the Problem:

Problems confronting the investigation of war gas deposits are not fully recognized to define the best monitoring procedures. From historical data, it is known that such deposits contain metal containers, barrels, grenades, artillery shells, and bombs. The grenades, shells and bombs contain explosives, and sometimes detonators and chemical agents, so they are very dangerous to handle due to the potential risk of leakage or explosion. The fact that it is not known which kind of the chemical agent has been placed inside (mustard gas, adamsite, LOST, Zyklon B or other type) makes all handling procedures even more dangerous. The largest deposits are east of Bornholm, at least 35,000 t (Bornholm Bassin); and South East of Gotland, about 2,000 t (Gotland Deep). Both areas are valuable fishing grounds. Due to this fact, a majority of incidents involving chemical war agents took place during recovery of fishing gear, where accidentaly caught ammunition camet into contact with humans. According to information obtained at experts' meetings, Danish fisheman have been catching 1 to 3 tons of war gas ammunition each year [3]. In a majority of these incidents, the dangerous catch was returned back into the sea immediately after discovery. In certain cases, the ammunition was again dumped into specially selected areas. [Source: Cmdr Soetofte Rep, Danish Navy, 1992). This latter approach agrees with expert and scientific opinion that refraining from recovering war gas ammunition from the ocean is the best and most harmless way to keep this war heritage relatively safe [3].

Having in mind all the security precautions, the survey of war gas deposits could be done in different ways. A typical scenario should consist of preliminary investigation by surface survey vessel. Mapping using a ship mounted or towed sonar system could collect information for AUV survey route planning. A bathymetric survey could bring valuable data about bottom three-dimensional coordinates which could help to plan AUV paths optimal from a data collection point of view. After analysis of collected data, potential targets could be selected for detailed AUV mission planning. Very important is to learn as much as possible about bathymetry, geology, geophisics, and oceanography of the investigated area. Precise mission schedule and motion energy consumption could be optimized, bearing in mind environmental conditions and specific data collection requirements. Moreover, the knowledge of AUV performance characteristics is crucial to mission planning procedures.

Task definition

From a practical point of view, data collection methods are similar to those used in mine countermeasures procedures. The difference is that bottom laid mines are often bigger and amagnetic. All information about those dangerous deposits could be classified into two groups:

- general information, like draft geographical coordinates, average surface density of deposits, deposit type - survey in a mesh step 1nm-1/100 oh nm - large mesh
- detailed information, like detailed geographical cordinates of target points, types of ammunition, corrosion destruction, and everything regarding particular mesh points in the war gas deposits area (step less than 11/100 of nm to 0.1m) - fine mesh

Actually, there is a lack of detailed information about distribution and condition of the chemical ammunition on the sea bottom. Some general information has been collected from various sources [3]. The known data include geographical coordinates of dumping sites, some data on ammunition type and war gas content. All these data are based mainly upon rare official reports, historical data and memories of people which participated in the operations. Quite a lot of information is still not available to the public -- hidden in Russian, British and American archives. Some monitoring projects were completed by Greenpeace, Danish Russian Expedition in 1994, but their results are hardly available.

From a monitoring point of view, lacking information includes detailed geographical distribution, 3-D picture of dumping sites, average corrosion status. This information could be obtained only with the help of precise instruments, using detailed investigatve methods. Certain types of instrumentation are not available and must be developed for use in AUV systems. An example could be detectors of war gases or their decomposition agents for u/w use. The safe and cost-effective way of information gathering is by application of robotic system for step-by-step data collection, starting from large mesh, having suitable reference points for reliable data comparision and analysis. After survey of selected areas using general methods, smaller areas for detailed investigation could be selected. The type of information required includes target mesh coordinates, ammunition type and their surface distribution, corrosion status, and danger status. A detailed bathymetry map is a prime requirement for AUV route planning when repeateable missions are cosidered at the same site. It is also highly recommended to integrate all initially available and collected data into a GIS-like data base.

AUV Mission Definition Criteria

AUV mission definition must be closely related to a number of factors. The most important of these are listed below. One could also identify other factors which, in every case, depend on specific survey requirements.

Table 1 Mission definition factors - MDF

General MDF	Detailed MDF	AUV Path	DCP	Emerg.
AUV hydrodynamic and energetical performance	Operational circle	M	L	M
	Obstacle avoidance charcteristics	M	L	H
	Motion characteristics	M	H	M
Work package characteristics	Available work package	H	H	L
	Data storage capacity	H	M	L
	Payload	M	H	L
	Information gathering procedure	M	H	L
Operational area description	Bottom bathymetry	H	M	M
	Near bottom currents	H	M	M
	Surface currents	L	L	M
	Water sound transmission characteristics	M	M	L
	Water light transmission characteristics	M/H	M/H	M
Operational support	Support ship facilities	M	L	L
	Available energy modules	H	H	H

L, M, H - Low, Medium, High - level of influence on MDF
DCP - data collection point
Emerg. - emergency procedures

The most critical factors for AUV task definition and mission planning are mission energetical requirements. State of the art allows for application of newly developed power sources with optimal energy density. Given a vehicle with certain dimensional restrictions and resulting weight/buoyancy figures, the overall AUV hydrodynamic and energetical data could be evaluated. Estimating potential work package requirements, like weight/ power characteristics, against available payload and power, the detailed mission definition could be evaluated and optimized.

The basic characteristics of the sea environment in the planned area of AUV operations is given below:

Table 2 Baltic War Gas Ammunition Dumps Operational Scenario

BASS AUV Operational scenario	
Baltic Sea	Bornholm Bassin (East of Bornholm) Gotland bassin (South of Gotland, South West of Liepaja
Depth	Bornholm Bassin: 40 - 90 m Gotland Bassin: 80 - 140 m
Sea state	2-3°B
Sea currents	0.2-0.3 m/s
Search area:	1x1 nm grid
Support ship:	small size R&D vessels c/w 1t crane

System selection

Underwater robotic systems are able to perform a variety of different tasks. Sea environment monitoring and suitable data collection are possible due to the large variety of equipment available and well known procedures (like STD, CTD). Application of tethered vehicles in sea environment monitoring is growing steadily. Particularly, towed undulating vehicles are used more and more frequently. On the other hand, tethered ROV's are used mainly by offshore industry. Their application for on line sampling is recognized for cases where other systems and methods fail (dunking bottom and water samplers, divers). Chemical analysis of water is a complex task and requires specialized instrumentation and clean laboratory conditions. Tracking traces of specific products of decomposition of chemical agents from gas ammunnition and containers underwater is a challanging task that cannot be done remotely. Obstacles include lack of instrumentation and recognized procedures. Water quality monitoring using autonomous vehicles could be conducted off line with the help of special water sampling devces preprogrammed and controlled by an AUV control algorithm.

Selection of the optimal data collection procedures during war gas deposits monitoring requires different criteria to be analysed. The most crucial of these are:

1. Data quality
2. Data amount
3. Real time data availability
4. Sampling system energy consumption
5. Risk of data loss
6. Risk of loss sensor carrying platform
7. Mission duration time
8 Operational costs
9. Sampling feasibility

Application of AUVs is justified in conditions where the use of tethered ROVs is less effective. As an example, one can consider the task of collecting water samples close to the bottom in an area larger than a tethered ROV footprint. Operating a tethered ROV system from the deck of a surface support vessel requires changing the vessel's position to move the underwater underwater vehicle into a new working area. A comparison of AUV and tethered ROV selection criteria is given in Table 3.

Table 3. ROV/AUV selection criteria

	Towed Vehicle	Tethered ROV	AUV
Real time control	No problem	No problem	Non available
Endurance	Very High	Very High	Limited by energy source
Payload flexibility	High	High	Limited by energy source
Risk of loss	Low	Low	Relatively high
Collected data quality	High	High	High
Collected data amount	Very high	Very High	Limited
Maneuvrability	Low	Very High	High
Area survey speed	Very High	Low	High
Suface Support Requirements	High	High	Low
Position reference	Easy - On line	Easy - On line	Difficlult
Bottom sampling ability	Possible	Very High	High

Following all security procedures and analyzing both AUV weak and strong points as well as considering all necessery AUV instrumentation, one can define mission targets and mission restrictions. Assuming the specifications of the Technical University of Gdañs BASS (Baltic Autonomus Survey system) project discussed below, two main tasks can be defined in cases of application of AUVs for war gas dumping site surveys:

1. Collection of visual and sonar images during circular cruise done as close as possible to the seabed in a predefined area where possibly high surface concentration of the war gas deposits has been detected by surface survey vessels.
2. Collection of bottom images and water samples from a distance closest to the located dumps using AUV water sampler from predefined locations (nodal points) lying on preprogrammed survey route. Water samples will by analyzed off line by a specialized chemical laboratory for traces of chemical agents resulting from chemical degradation of war gas chemicals.

BASS AUV Operational Characteristics

The general arrangement of AUVs is given in the Fig.1., and general characteristics in Table 4.

Table 4 General Characteristics of BASS AUV

Dimensions LxBxH:	4x1x1 m
Weight	300-400 daN
Range	10-20 nm
Speed	0.5 - 1.0 m/s
Navigation equipment	ST525 sonar ST200 echosounder Doppler Velocity Sonar ORE LXT u/w navigation system DGPS
Tool set	U/W TV camera Side scan sonar - option Still camera c/w strobe - anaolog option Digital still camera - option Water sampler - option STD probe - option Dissolved oxygen probe- option pH - option Fluorometer - option
Battery capacity	Total: 2000 Wh Motion system: 100-200 W/h Navigation: 20-40 W/h Tools: 30-150 W/h
Options	Fiber optic data comms link for surface vehicle control

Two potential missions scenarios are given in Fig 2. and Fig. 3. In both cases, a reference Ultra Short Baseline u/w transponder with acoustic release is placed on the bottom in the selected area. U/w navigation system position data output is related to surface based DGPS system on board the support ship.

Other operations could be conducted using AUVs, but this requires more specific analysis. An example of such a task could be collection of bottom samples in close proximity to war gas shells or containers. While there is an evidence that mustard gas could be found as separated lumps, there is a quite high potential risk that very dangerous samples could be collected in the automatedl sampling mode. The vehicle could be contaminated with toxic agents and suitable decontamination procedures must be carried out following the completion of each mission on the deck of the surface support vessel. Ground sampling using a tethered ROV manipulative system are reccomended for such operations, but this is a separate and very complex problem from a safety pont of view. Some chemical shells contain detonators and explosives, and no one knows the true content of objects of interest.

Tool set requirements

There are diffrent ways to conduct the task. Data amount and quality are determined by mission requirements and the tool set specified. Potential mission types can be identified as follows:

1. General tv/sss survey
2. Detailed tv/photo survey
3. Detailed tv/photo/sonar survey
4. Detailed tv/sonar/ water sampling survey
5. Detailed tv/photo/sediment sampling survey
6. Detailed tv/photo/water/ sediment sampling survey

The instruments specified and integrated into the AUV system should have an energy consumption as low as possible and data recording and storage capabilit as high as possible. The following data collection formats are envisaged. Digital data storage is optimal for post mission processing and data fusion. In certain cases (continuous TV path recording, still pictures), analog data format provides some advantage due to resolution and amount of information content. All data should have suitable position and vehicle status references.

Other potential problems and requirements

While war gas dumping sites contain explosives and dangerous chemical compounds, suitable means must be envisaged in the following emergency situations:

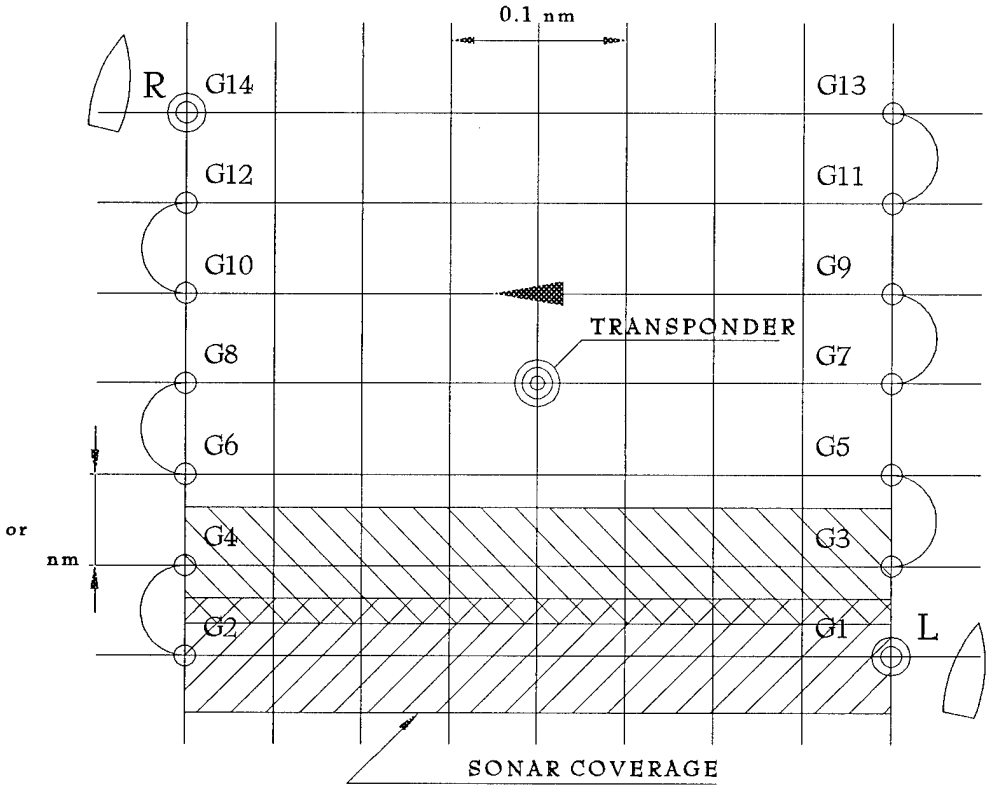
1. Recovery of bottom sediments due to accidental collision with war gas lumps
2. Detection of contaminated water samples

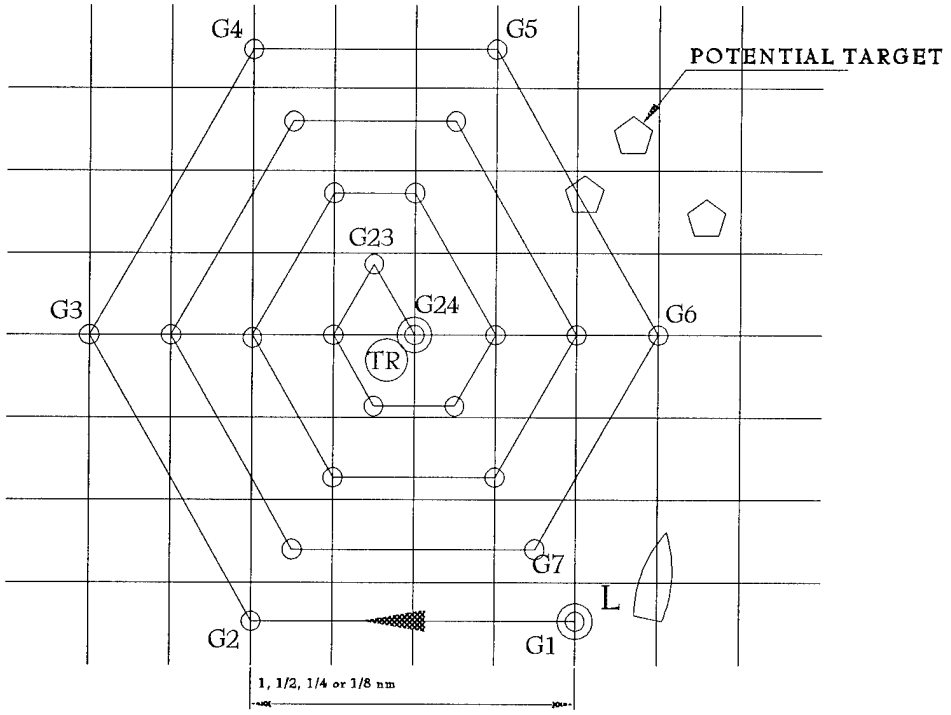
In both cases decontamination equipment should be available and decontamination procedures must be applied on board the support vessel. This risk is also a factor which should be considered in AUV design and subsystem integration. Another problem which must also be analysed and solved is insurance coverage for the AUV, operating personel and support ship against all potential risks critical for successful mission performance.

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2 Dumps of the Deep, The Sunday Times Magazine, April 5,1992.
3. Risk Assesment of Military Waste Dumped at the Baltic Sea Floor, Materials of the European Experts Workshop, Kiel, June 2-4, 1993.
4. Baltic Autonomous Survey System - BASS, Control System Design and Procedures, Unpublished Report, Faculty of Ocean Engineering, Technical University of Gdansk, 1996.


0.1 nm
R
G14
G13
G12
G11
G10
G9
TRANSPONDER
G8
G7
G6
G5
or
nm
G4
G3
G2
G1
L
SONAR COVERAGE


G4
G5
POTENTIAL TARGET
G23
G3
G24
G6
TR
G7
L
G2
G1
1, 1/2, 1/4 or 1/8 nm

The Lemmings/BUGS System

Arnis Mangolds
Foster Miller, Inc.

Lemmings is a DARPA Phase II SBIR which uses many small, inexpensive autonomous bottom crawling vehicles to achieve any number of very shallow water, surf zone or land missions. Originally designed for mine hunter-killer applications, the concept has grown to address anti-invasion obstacle neutralization, reconnaissance, and mapping. Foster-Miller has designed a complete system which includes vehicle mobility, sensors, coverage, and payloads. In this presentation, we will address the issue of mobility, which is a tradeoff mission logistics and goals. The Lemmings system has been adapted to several missions, including a 'mini version' which allows large numbers to be fit within a 21-inch tube, a 'standard version', and a larger Sea Dog unit which can accommodate large payloads. The presentation will discuss tested ranges, operation in different subsea and landbased environments, and the incorporation of 'anti-social' systems to permit multiple Lemming operation in a confined environment.

Because a full paper was not received by publication date, the above Abstract appears in this Proceedings. Mr. Mangolds can be contacted at Foster Miller, Inc., 350 Second Avenue, Waltham, MA 02154-1796; telephone 617-684-437; e-mai <amangolds@foster-miller.com>.

Application of the Explosive Ordnance Disposal Robotic Work Package to the Clearance of Terrestrial Improved Conventional Munitions (AutoRECORM)

Gary M. Trimble
Lockheed-Martin/Ocean, Radar and Sensor Systems Division

The Explosive Ordnance Disposal Robotic Work Package (EODRWP) is being applied to the automation of the Remote Control Reconnaissance Monitor (RECORM) terrestrial surveillance vehicle in support of the area survey, detection and automated classification of improved conventional munitions as a precursor to actual clearance operations by alternate robotic assets or EOD personnel. Capabilities being rehosted or developed under this program will increase effectiveness of application of the RECORM or equivalent terrestrial surveillance vehicle by leveraging the EODRWP "intelligent" control architecture to support directed semi-autonomous and fully autonomous operations. Automated perception processing provides for the integration and correction of sensor data, image segmentation, feature extraction, and object recognition, and supports classification of potential ordnance through the evaluation of information from complimentary sensors. Current efforts focus on the adaptation of the EODRWP mission/vehicle control capabilities to the terrestrial application through the modification of domain specific knowledge, which facilitates user-defined mission plans; development of the interface to the RECORM motor controllers; replacement of the underwater vehicle's acoustic navigation system with a Global Positioning System receiver and interface via radio-modem, which takes advantage of the increased autonomy. This further reduces operational complexity by supporting user interactions with the vehicle via a graphical interface on the control station to allow for simultaneous operation of multiple AutoRECORM vehicles in conjunction with other clearance/neutralization assets by a single operator.

Because a full paper was not received by publication date, the above Abstract appears in this Proceedings. The author can be reached at Lockheed-Martin, telephone 408-742-7596.

CHAPTER 6: COUNTERING MINES ON LAND

The papers grouped in this Chapter deal with technologies and systems that seem most relevant to the military problem of Land Countermine operations. Many of these applictions could also be relevant to Humanitarian Demining, or to the companion military problem of countering mines at sea.

Technologies and systems for countering mines on land must advance the objective of reducing the risks from mines to levels commensurate with the risks to a military force from other types of enemy action. Furthermore, the approaches must help meet the stringent time parameters that attend minefield breaching under conditions of land combat. Even in what is called "administrative countermine operations" (clearing of rear areas for depots, etc.), field operators often face severe time constraints.

In general, systems for the land countermine operations will be operated by trained military personnel. While administrative operations may be in areas relatively immune from hostile fire, the breaching operations are assault operations. The expectation that trained military personnel will be the users helps the developer know what kind of logistics support and maintainability criteria must be met.

Candidate technologies and systems for the Land Countermine operations must demonstrate capability in most, if not all, physical land environments. What works in the desert may be totally inappropriate for application in Bosnia's forested regions. Sensors are particularly sensitive to the physical environments in which they are employed. The effects of the environments will be demonstrated during the exercises that constitute the Advanced Concept Technology Demonstrations (ACTDs) slated for '97 and '98.

The physical environments of Mine Warfare so dominate the technological solutions to the Problem that the 1998 Symposium on Technology and the Mine Problem will call for papers on the land and sea operational environments.

As in medicine, there is no approach that meets all requirements -- no "Silver Bullet". Rather, there must be sets of tools that, in the hands of the military engineer, can be used to carry out the necessary operational tasks.

Opening Remarks by Chair of Session XV, "Systems and Technologies for Countering Mines on Land"

COL Robert Greenwalt, Jr., USA
Director, Combat Developments
U.S. Army Engineer School

Systems & Technologies: Dealing with the Delta

- Use Risk Management Process
- Employ all mine countering techniques, not just detect and neutralize
- Base technological requirements on operational parameters!



UNITED STATES ARMY ENGINEER CENTER

STATUS OF COUNTERMINE MATERIEL SYSTEMS

- **CURRENT SYSTEMS**

  PROBE

  METAL DETECTOR

  ROLLER

  FLAIL

- **NEAR / MID-TERM** *"NO SILVER BULLETS"*

ESSAYONS "Let Us Try"



UNITED STATES ARMY ENGINEER CENTER

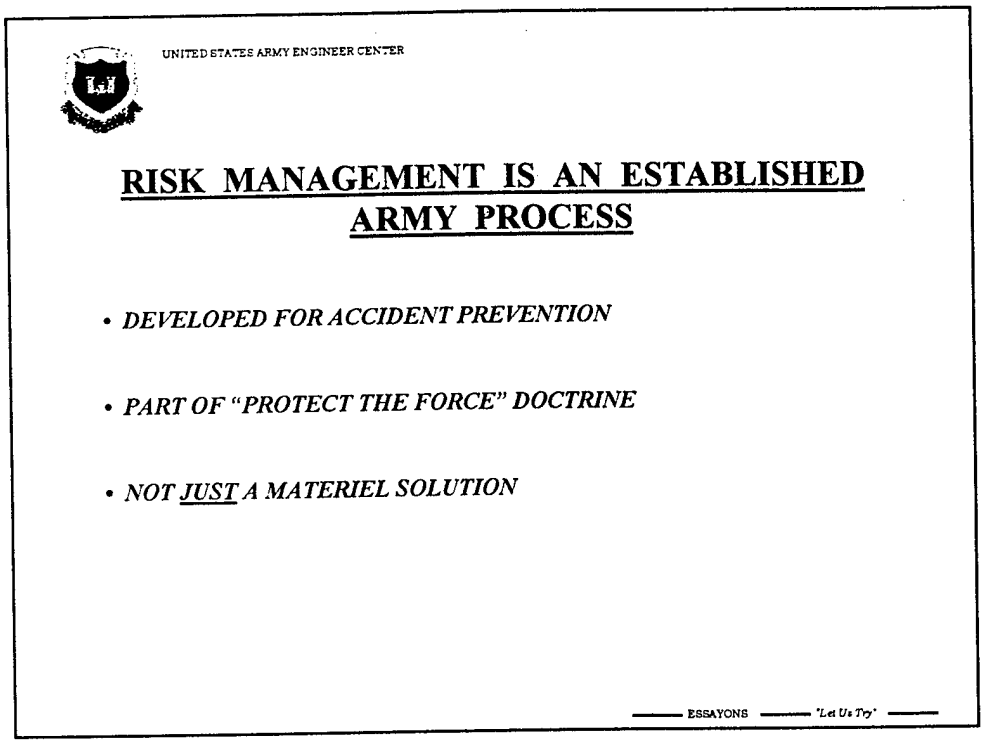
LIVING WITH THE DELTA

(RESULTING FROM IMPERFECT SYSTEMS)

- ***GAMBLE***

- ***USE RISK MANAGEMENT***

ESSAYONS — *"Let Us Try"*

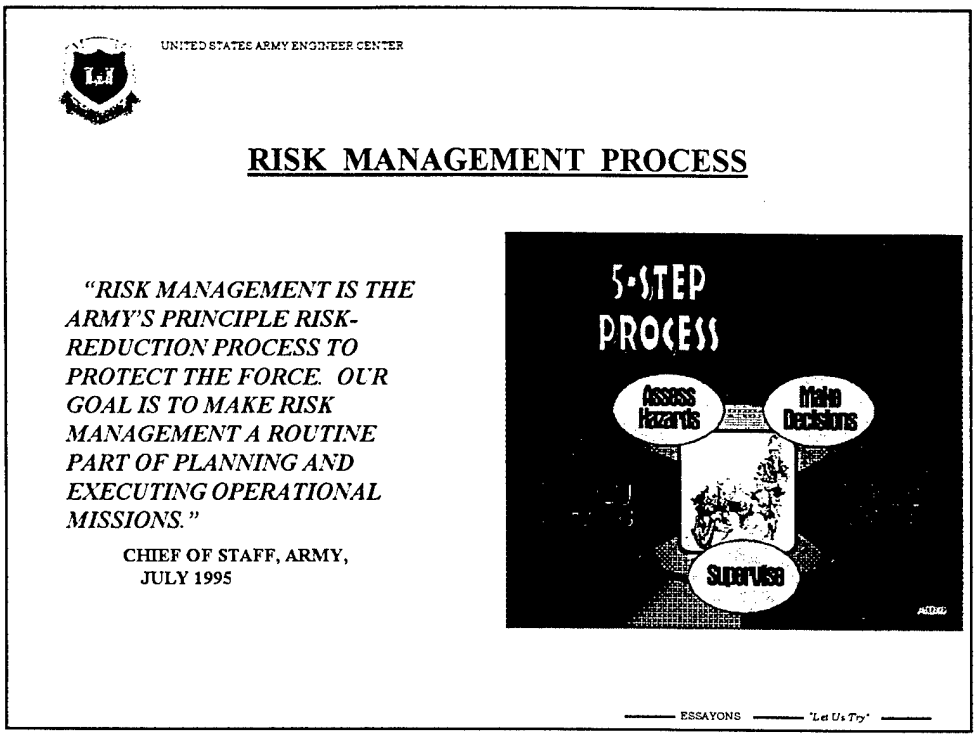


Has been instrumental in recucing Army accident rate by 75% over last 10 years.

Already an established procedure for tactical commanders. They need the tools/information to be able to integrate the mine related hazards into their tactical planning.

Risk Management is enhanced by materiel solutions but more dependent on understanding what the hazards are,knowing the resultant risk, and employing appropriate controls.

We need your help so we can make it as effective in Countermine Operations as in accident prrevention.



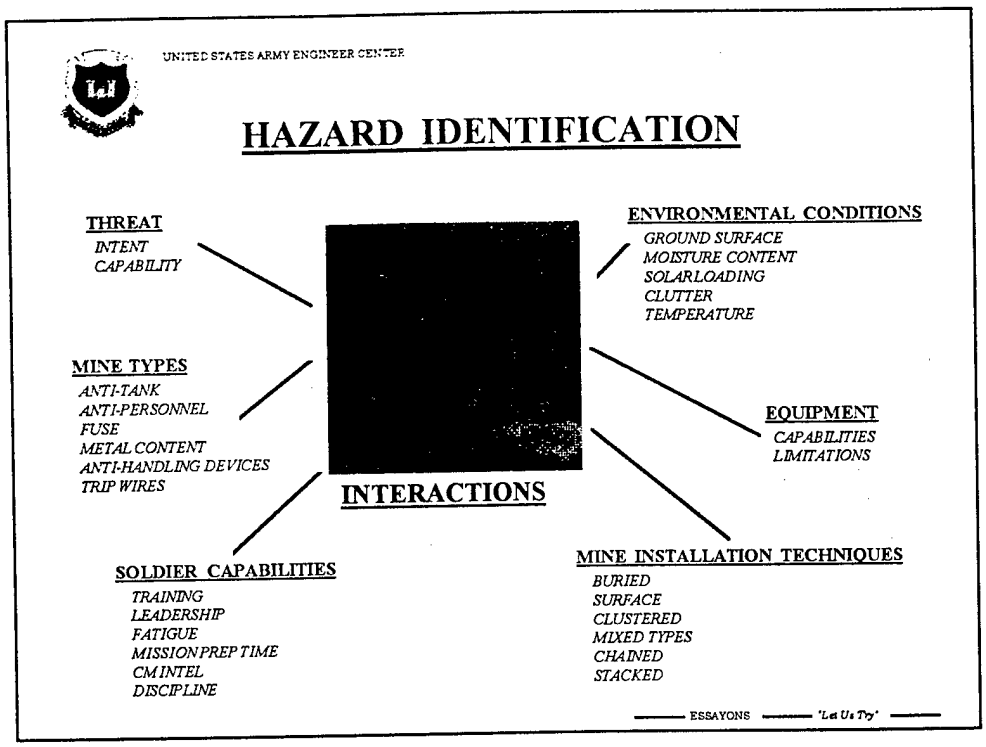
Identify the hazard - most difficult part of Risk Management. Based on professional judgement and lessons learned.

Assess the hazards - determine the risk by evaluating the probability and the severity of mine strike or other undesirable event.

Make Decisions - determine what risks are acceptable and which ones must have controls applied to reduce the probability and/or the severity to acceptable levels.

Implement Controls - simple the act of applying appropriate controls to the unacceptable risks. Could be changes to any part of DTLOMS.

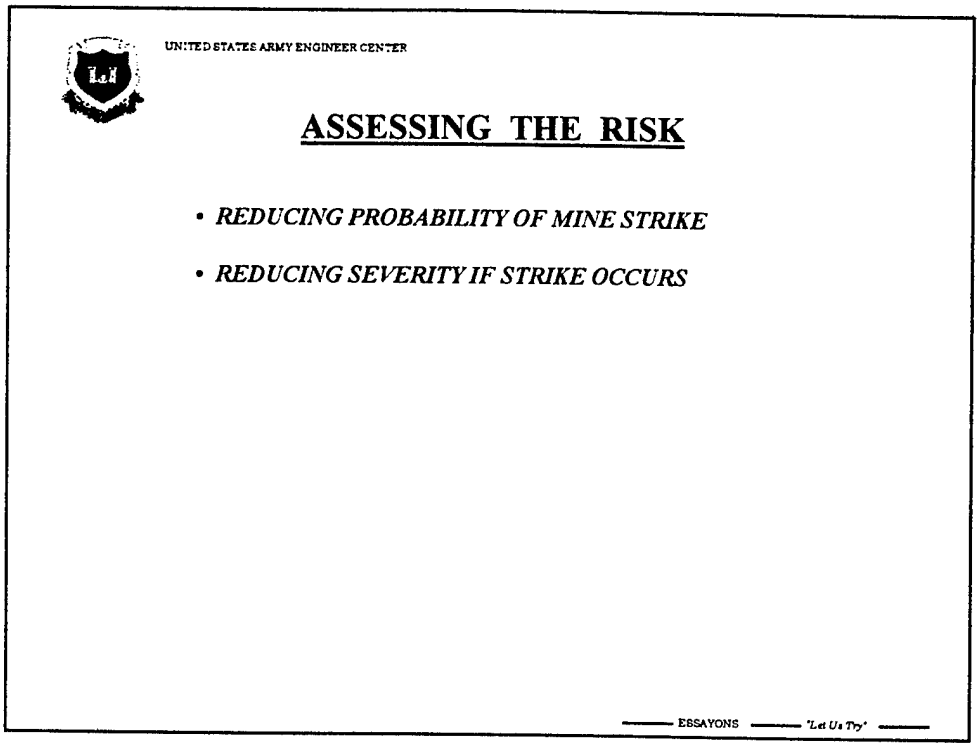
Supervise - ensure that controls are applied.



Hazard is any real or potential condition that can cause injury or death to personnel or damage to or loss of equipment.

The interaction of conditions may greatly increase the likelyhood of mine strike/undesired event.

Since usually dealing with low probabilities (but high severities) with many interacting variables, human has limited capbility to accurately assss.



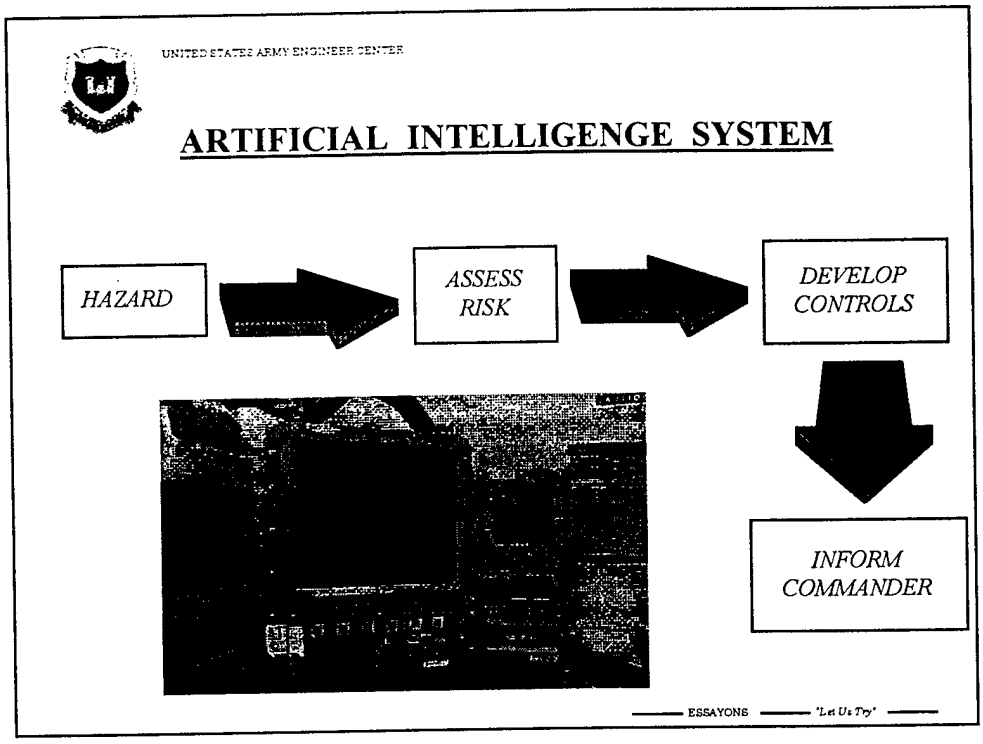
Objective in this process is to evaluate the hazard to determine the probability of it occurring and the severity/effects if it does occur.

If probability is low enough catastrophic severity may be acceptable (falling meteors are little concern). If severity is low enough probability is discounted, AP mines are not a high risk for armored vehicles.

Controls are normally used to reduce one or the other.

Much of our focus in countermine has been in detection (reducing the probability). Given limitations with current technology, developing protection to reduce severity may be more appropriate.

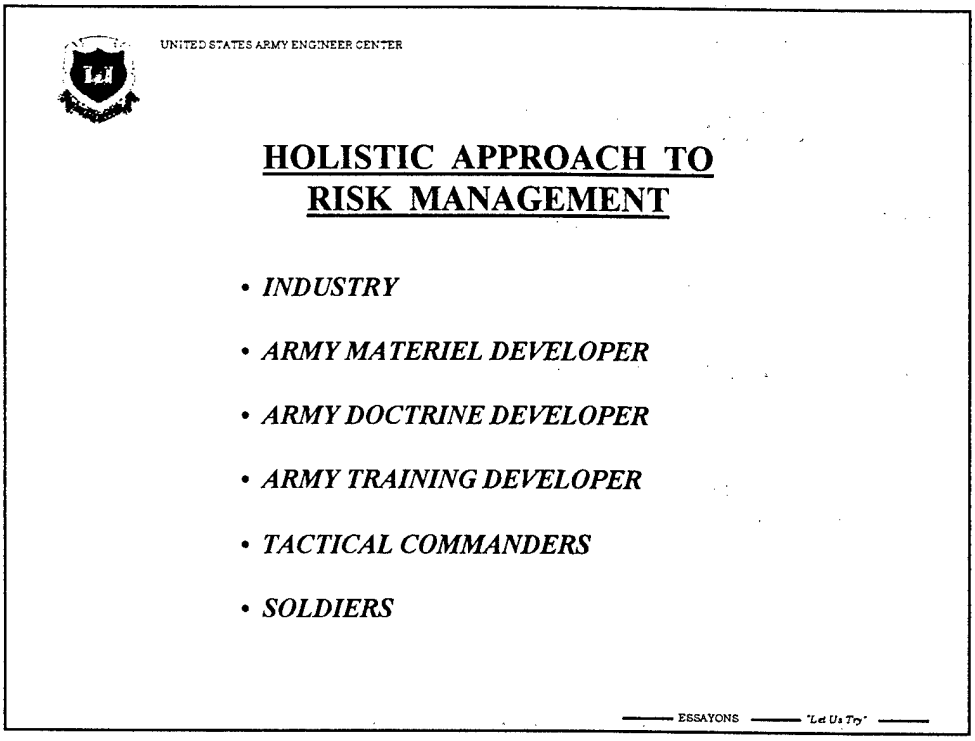
Panther is useful in part because of very low severity.



An artificial intelligence system is needed to assist commanders in process the large quantity of information needed to optimize risk management.

A night rotary wing Automated Risk Assessment and Contol (ARAC) system has already been developed. Other automated systems are currently underdevelopment.

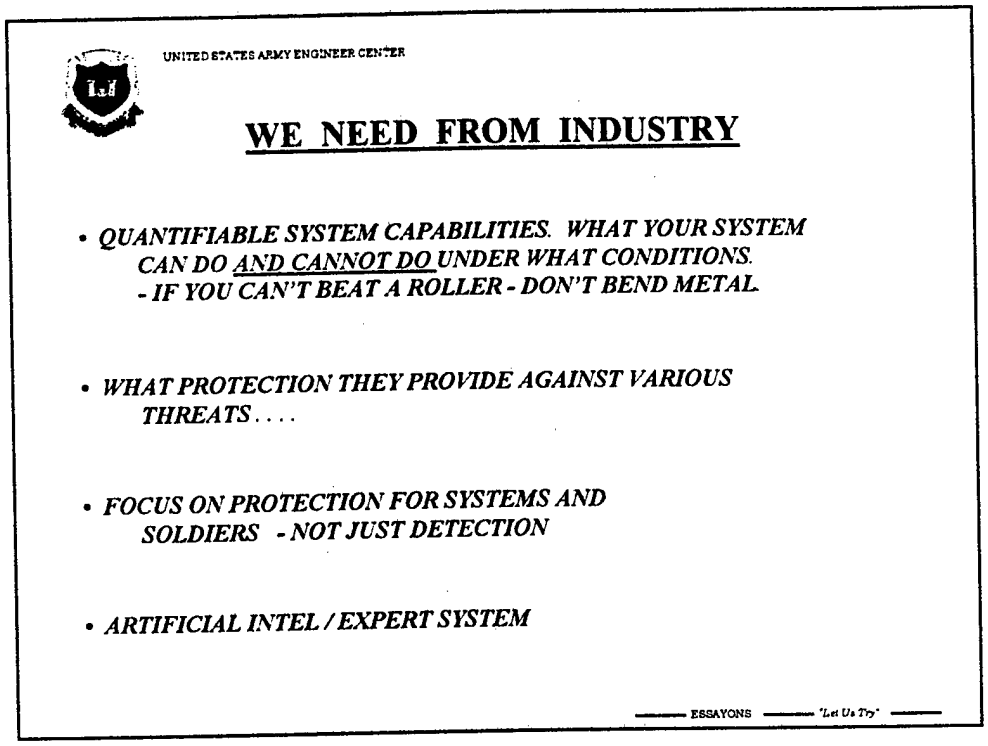
Will enable to commander to combine information from many sources to most accurately identify hazards, assess risk, and develop controls.



Up to now have been discussing risk management at the tactical level. But risk management must occur all the way from industry down to the soldier in the field.

We (industry and the materiel) must develop a countermine component to the each system's system safety engineering program. We continue to field tracked and wheeled vehilces with little protection from mines. Few energy absorbing crew seats and little or no consideration for blast deflection away from the crew compartments.

Mine related hazards that can not be designed out of vehicles must be made known to the doctrine and training developers. By changing the way we operate in the field we may be able to reduce the mine threat. Controlling soldier behavior through training and discipline has been instrumental in keeping mine incidents extremely low in Bosnia.



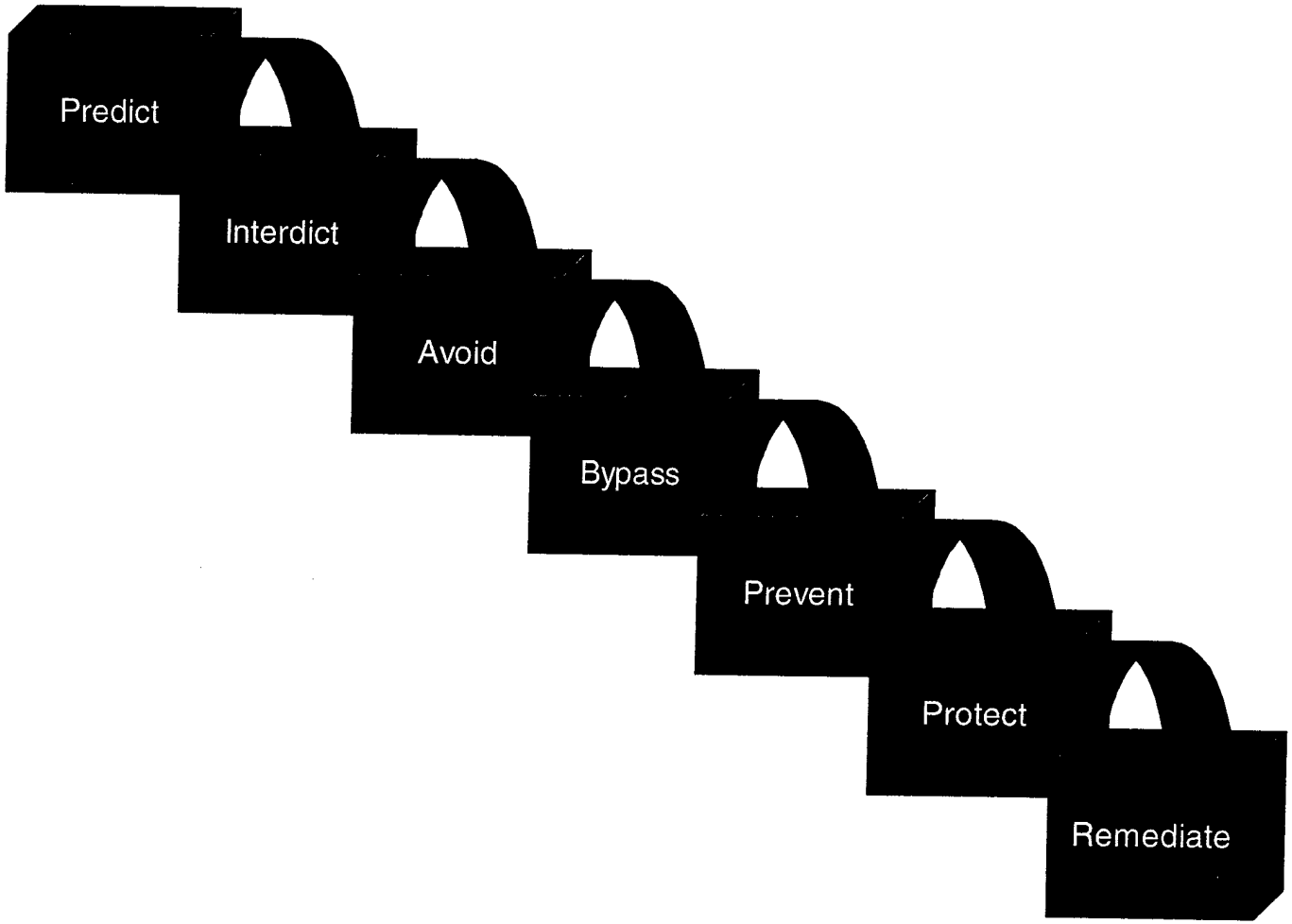
We need accurate information on how well your systems will function in the conditions that we work in. Capabilities and limitations finding the multitide of mine types. With artificial intelligence commanders can use technical information.

We need to know the tolerance of systems to mine strikes and how well the operators are protected.

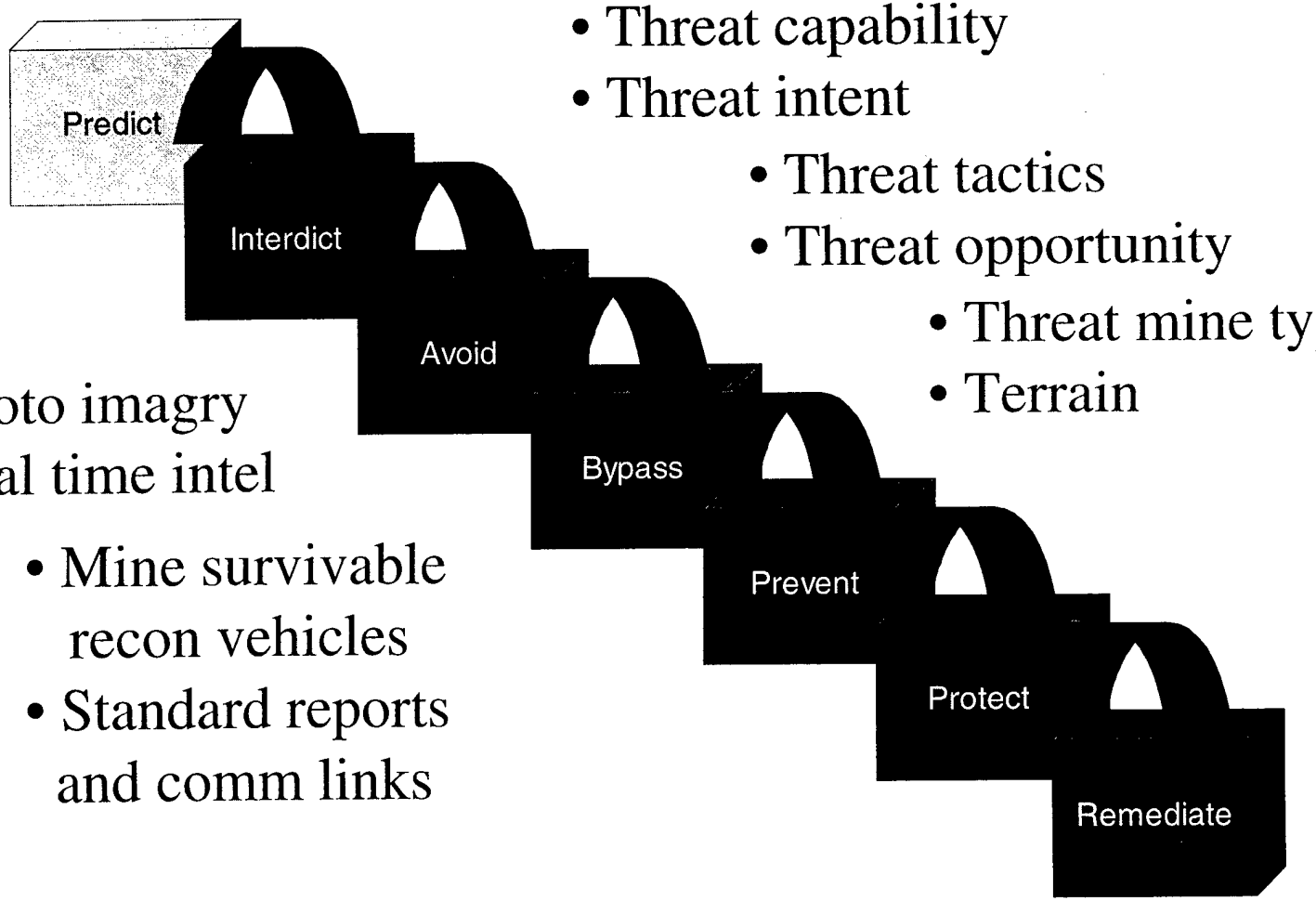
We need more effort on protection. Detection may be more difficult and expensive then protection - particularly for some missions.

We need help in developing an artificial intelligence system. Must have defined capabilities of any systems we employ. Must also consider the hundreds of combinations of conditions that make up hazards from mines. Our information on lessons learned and your help with capabilities will be a start for this.

Mine Countering Techniques



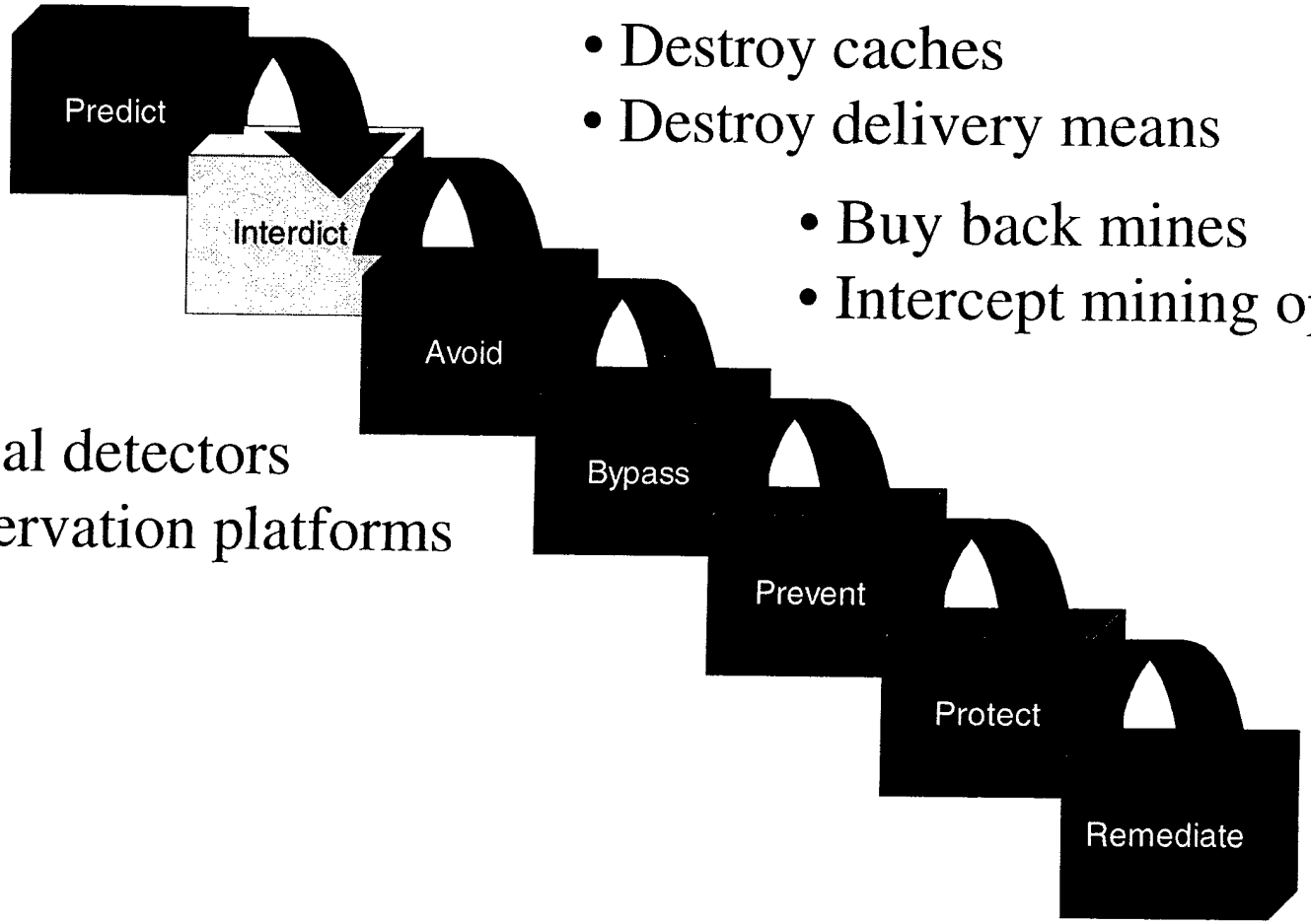
Route Countermine



- Threat capability
- Threat intent
  - Threat tactics
  - Threat opportunity
    - Threat mine types
    - Terrain

- Photo imagry
- Real time intel
  - Mine survivable recon vehicles
  - Standard reports and comm links

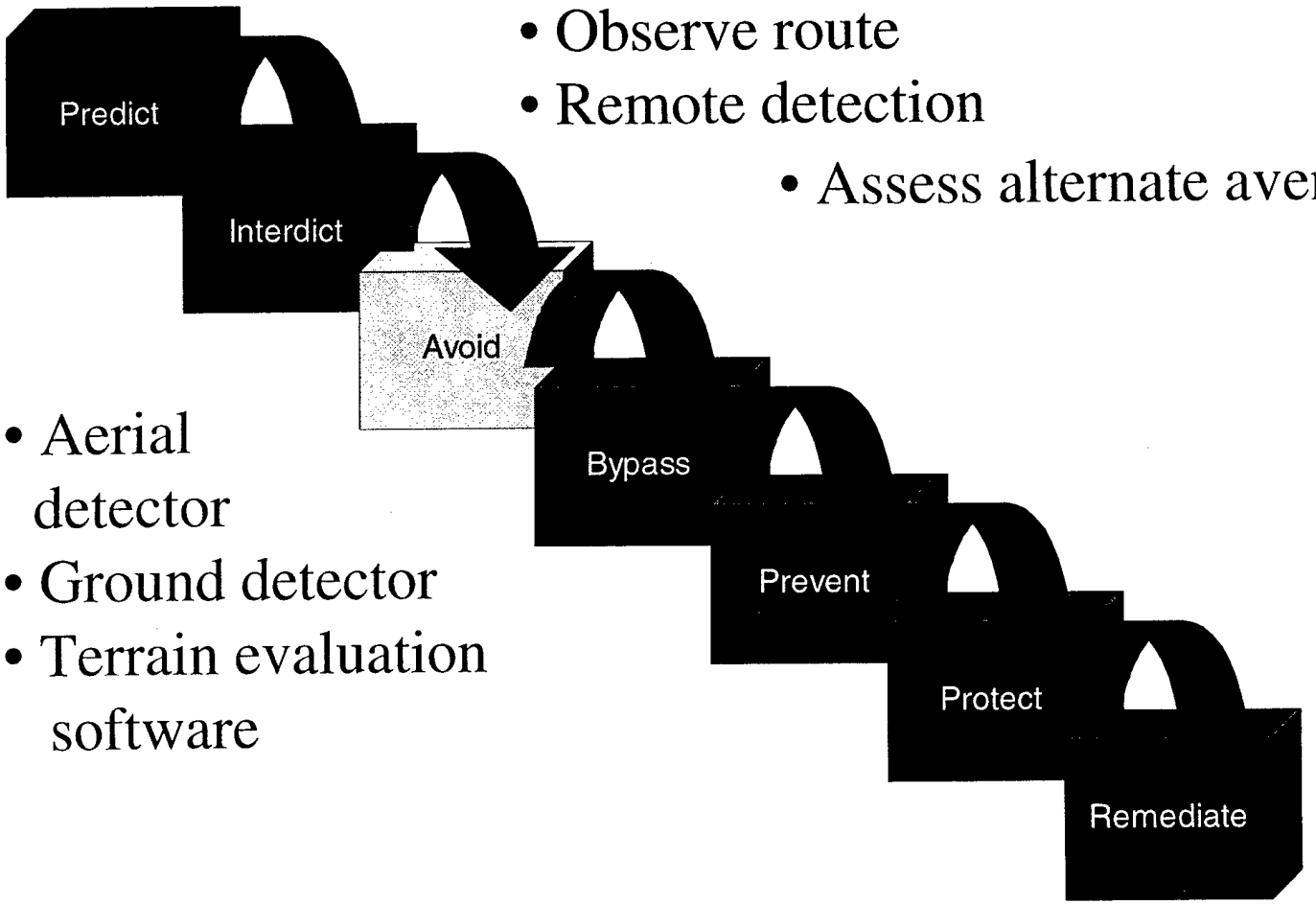
Route Countermine



- Destroy caches
- Destroy delivery means
- Buy back mines
- Intercept mining operations
- Aerial detectors
- Observation platforms

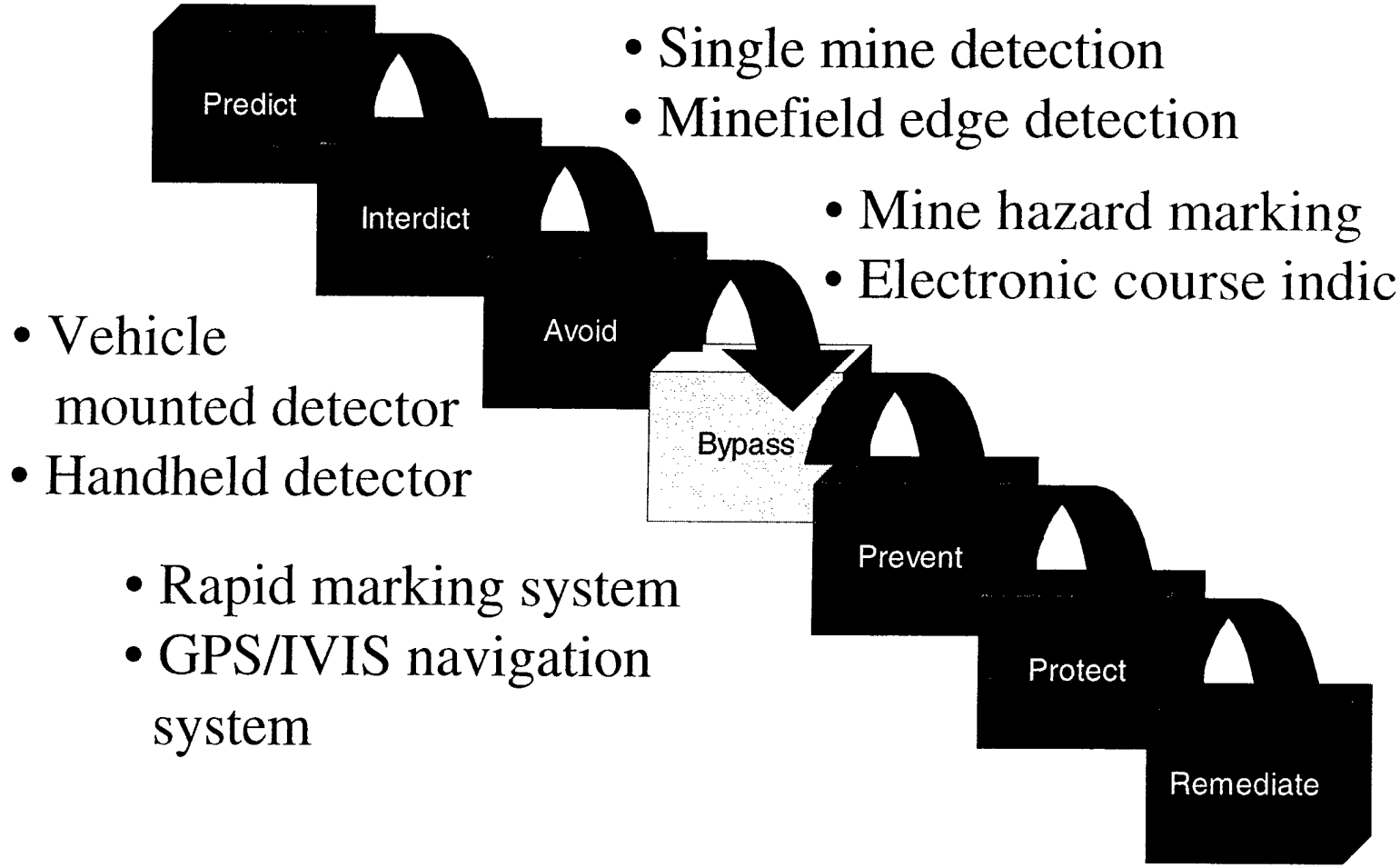
Route Countermine

- Observe route
- Remote detection
- Assess alternate avenues



- Aerial detector
- Ground detector
- Terrain evaluation software

Route Countermine



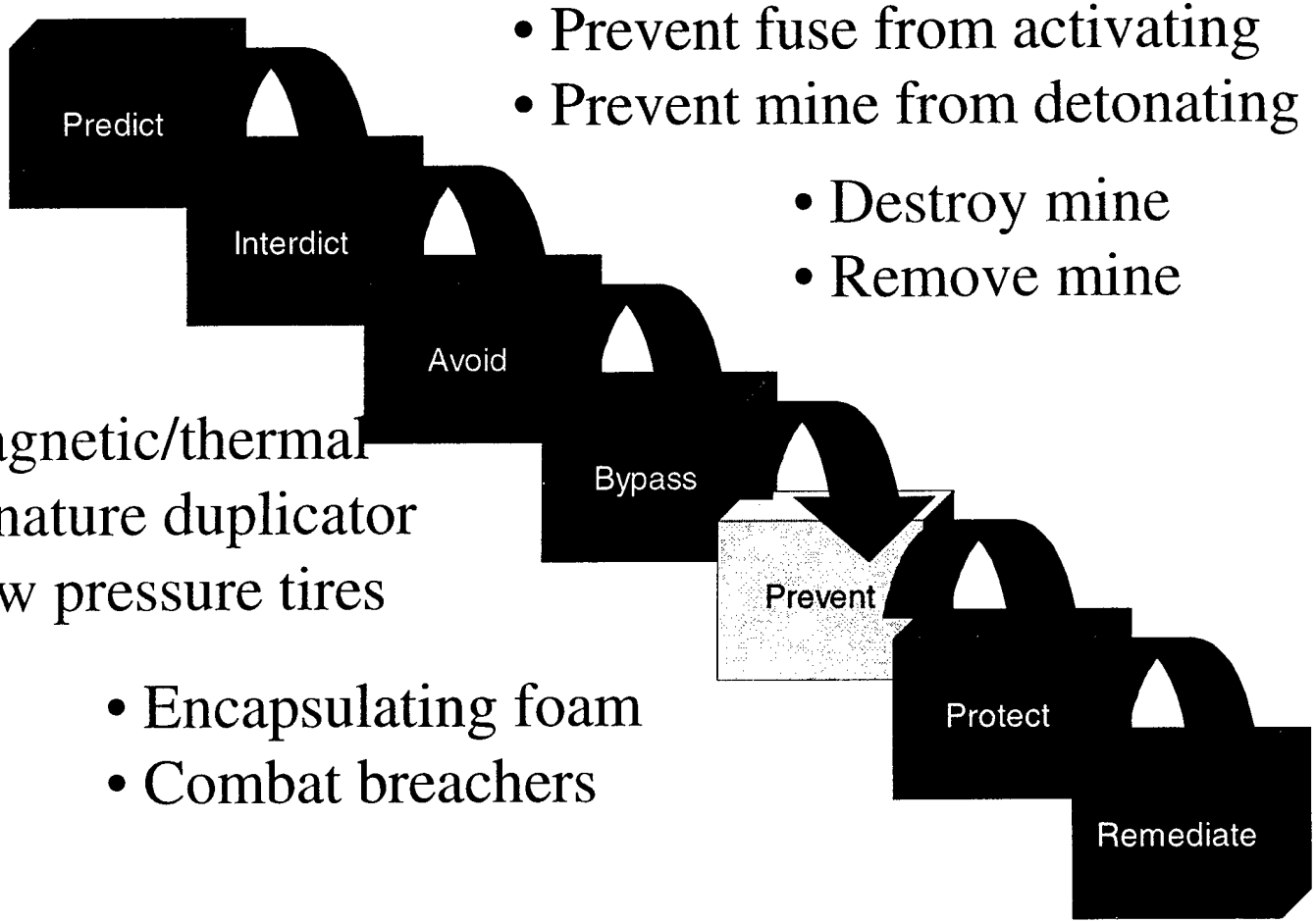
- Single mine detection
- Minefield edge detection

- Mine hazard marking
- Electronic course indication

- Vehicle mounted detector
- Handheld detector

- Rapid marking system
- GPS/IVIS navigation system

Route Countermine



- Prevent fuse from activating
- Prevent mine from detonating

- Destroy mine
- Remove mine

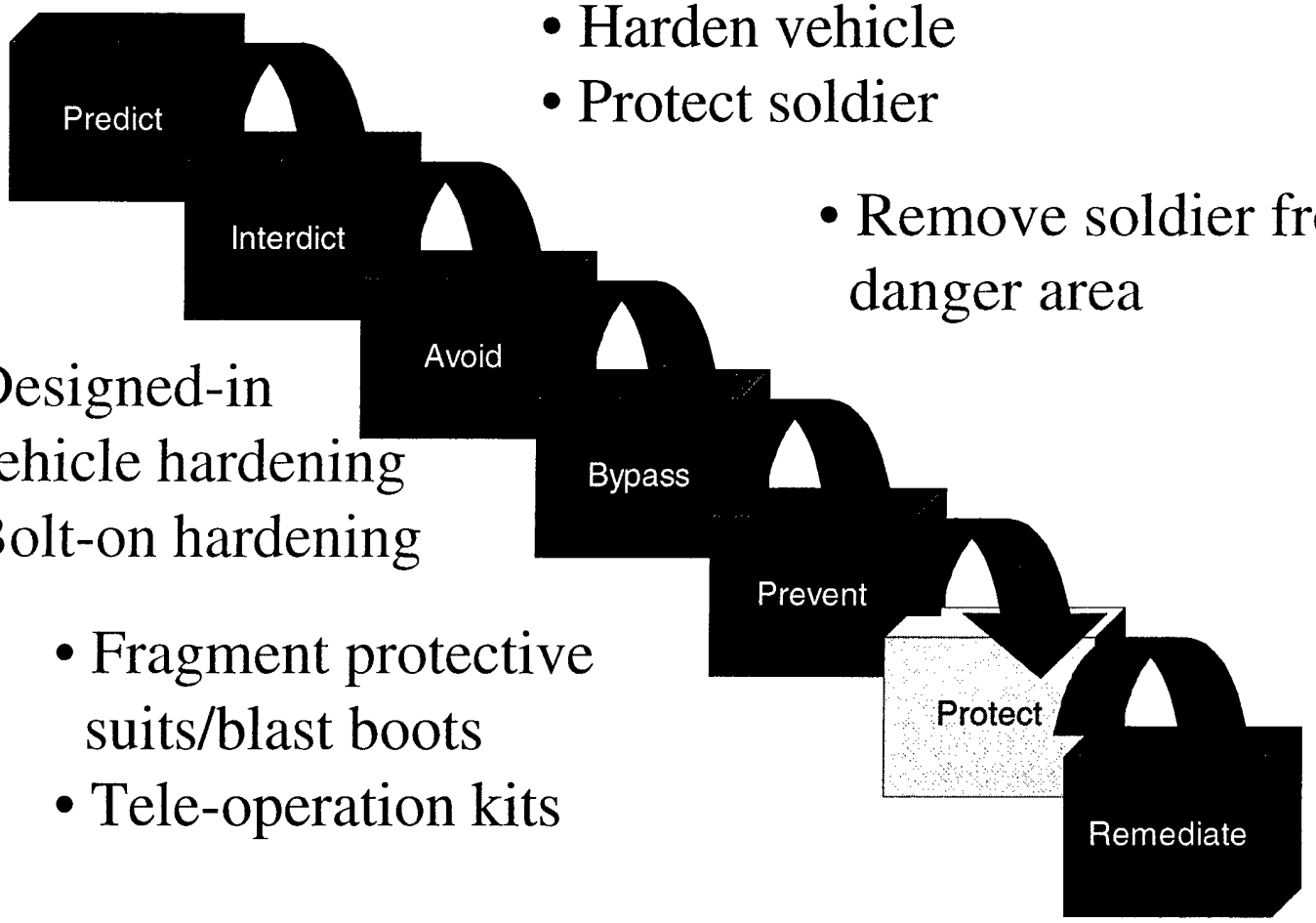
- Magnetic/thermal signature duplicator
- Low pressure tires

- Encapsulating foam
- Combat breachers

Route Countermine

- Harden vehicle
- Protect soldier

- Remove soldier from danger area



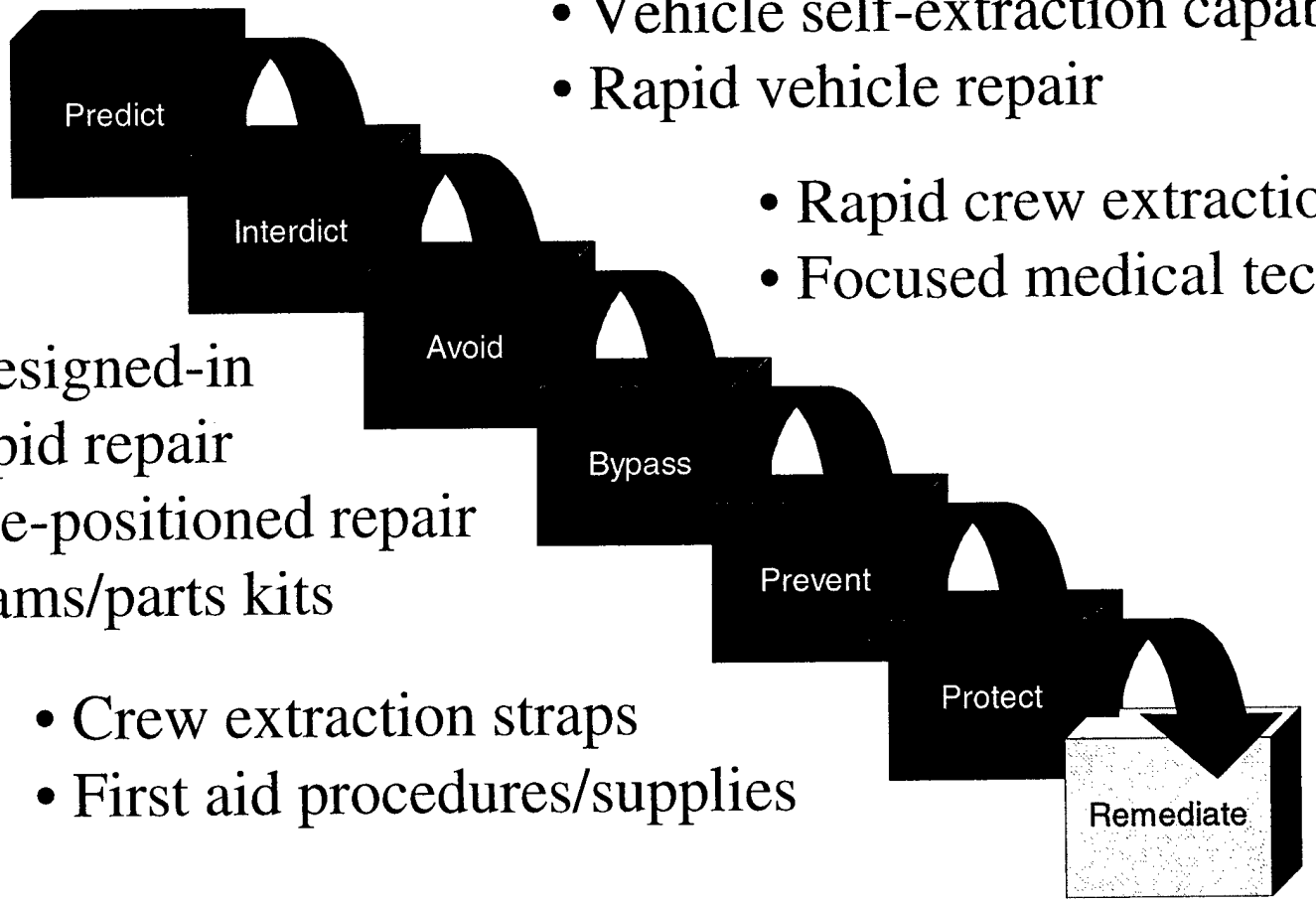
- Designed-in vehicle hardening
- Bolt-on hardening

- Fragment protective suits/blast boots
- Tele-operation kits

Route Countermine

- Vehicle self-extraction capability
- Rapid vehicle repair

- Rapid crew extraction
- Focused medical techniques



- Designed-in rapid repair
- Pre-positioned repair teams/parts kits

- Crew extraction straps
- First aid procedures/supplies

Route Clearance Requirements Base Case

Tank Roller: Pd = 100%
FA = 0%
Speed = 15 km/hr

Route Clearance Detector

Pd = 100%

FA = Route opening speed remains 15km/hr

If detector operates at 40 km/hr,
allows 37.5 minutes to deal with FA

If FA requires 5 minutes to eliminate, can handle 7.5/hr

15 km x 3m detector = 45,000m^2
45,000/7.5 = <u>1 FA/6000m^2</u>

Route Clearance Technique?

Mark and continue when detect anomaly

Assume FA = 1/30m^2

15km x 3m = 45,000 m^2
45,000m^2/30m^2 = 1500 FA/hour

1500 x 1.25lbs C4 = <u>1800lbs C4/hour</u>

1500 x 5 minutes = <u>125 manhours/hour</u>

Route Clearance using Dorbyl

Pd = 100%
Speed = 40 km/hr
Mine strike requires 30 minutes for repair

Route opening speed remains 15 km/hr -- allows 37.5 minutes to repair mine strike damage

37.5minutes/30minutes = 1.25 strikes/hour

If detector head has Pd = .7
1.25/.3 = can handle 4.2 mines/(hour or 15 km)

Symposium on Technology and the Mine Problem, Monterey, 18-20 Nov 96

GPR and Metal Detector Portable System

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Abstract

DeTeC (Demining Technology Center) is developing a sensor system for humanitarian demining, which reduce the number of false alarms and can be carried by a man or an autonomous lightweight robot.

The objective is to reliably recognize minimum metal antipersonnel mines. A metal detector is used to recognize the location of objects with some metal content. A GPR then provides an image that allows to differentiate a mine from metallic debris. The efficiency of deminers using the combined detector should increase significantly, and the database that can be built at the same time is essential for further steps in automating the search process.

Initially, deminers will look at the GPR images as an optional information, not changing their SOP (Standard Operation Procedures). They should progressively get confidence in the displayed information, which they can relate in real time with the result of their prodding.

1. Introduction

The metal detectors currently used by demining team cannot differentiate a mine from metallic debris, which sometimes leads to more than 1000 false alarms for every real mine found. Although the detectors can be tuned to be sensitive enough to detect the small amount of metal in modern mines, this is not practically feasible, as they will also be sensitive to ferrous soils, leading to the detection of smaller debris and augmenting the false alarms rate. Nowadays, once an alarm is given by the metal detector, the soil is prodded at a shallow angle using rigid sticks of metal to determine the shape of an object; this is an intrinsically dangerous operation.

The need for new, efficient and affordable demining technologies and sensor systems is therefore obvious. An overview of the current research status is given in [Maechler95] and [Gros96]. Past conferences dealing with this problem are listed in [Nicoud96b].

2. The DeTeC test system

Extensive tests in a "sand box" are required to develop the filtering and recognition algorithms, under repetitive conditions. Two containers have been built, one filled with sand and the other with loamy soil; they are 1 metre deep and 3.5 by 3.5 metres wide (Fig 1). A cartesian gantry positioning system allows to move the sensor above one of the containers at a time. Vertical motion is not controlled: the sensor is set at a fixed height, or a spring adjusts the pressure on the ground. The stepper motors control box receives displacement orders from a serial line, and the acquired data is stored on a PC's disk and transferred later to some server. Most of these measured data files are available on our Web site.

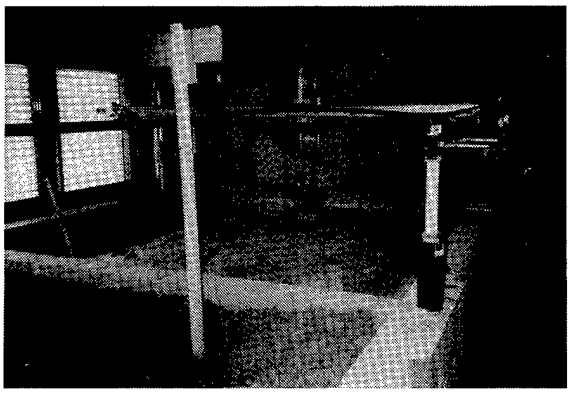


Fig. 1 DeTeC test system: sand box, cartesian robot, 1 GHz radar antenna.

More realistic tests will be carried out at a later stage in the open. The cartesian positioning system is in fact easy to dismantle and carry. It just needs 4 support points for installation and can operate with the PC from a small power generator.

Tests are made with original inert mines and replicas, both very difficult to obtain. The explosive is replaced with wooden pieces of the same form, or explosive simulants such as beewax, or Dow Corning RTV 3110 and 3112 silicone rubbers [Bruschini96].

2. GPR selection

Current GPR systems are still way too expensive to be used in large number for humanitarian demining, such as it is now done with metal detectors. But we hope that prices will fall when the efficiency for mine detection will be proven and when the manufacturers will realize the potential market available.

A GPR for antipersonnel mine detection must have a wide frequency band to achieve a good resolution, but since higher frequencies do not propagate well, the chosen range is always a tradeoff between resolution and penetration depth. For antipersonnel mines (AP), a center frequency of 1 to 2 GHz, and a bandwith of the same magnitude, seem to be a good choice for most types of soil and for APs with a diameter of 8-10 cm. Smaller mines might require correspondingly shorter wavelengths, which will shorten the usable depth range too, but they are also buried closer to the surface.

A. Hardware

The radar choosen for our experiments is a SPRScan commercial system made by ERA Technology (UK). The acquired data is displayed in real time as a scrolling B-scan on the LCD screen of a rugged 486, 66 MHz PC. The antenna has a nominal bandwidth of 800 MHz to 2.5 GHz, which leads to an expected resolution of less than 5 cm.

All data are directly stored on the internal hard disk of the GPR and after that, files are transferred to a separate PC for data analysis. Most of them are freely available on Internet at
http://diwww.epfl.ch/lami/detec/gprimages.html
(SEG-2 file format used by the radar). Objects measured are antipersonnel mines and false positives (stones, bricks, wood and pieces of metal buried up to 30 cm). All these data are stored in one database and serve as input for algorithm evaluation.

B. Software

Software embedded in the radar is limited to some basic functions, mainly designed to improve the image quality and it is not sufficient for antipersonnel mine image analysis. Affordable GPR software for real-time applications seems not to be available on the market. Systems developed for military use are often mentioned, but are usually either classified or prototypes.

To start with, we have selected the Reflex seismic off-line processing package. Several modules are available for data analysis. Algorithms not included in Reflex are developed using the Matlab environment. Now, all the required modules are rewritten in Matlab, to allow us to evaluate all the modules of the data processing chain. The next step will be to rewrite all the routines for a fast DSP.

C. Data Visualization

Different visualization techniques are being evaluated to find the most suitable one, from a practical and computational point of view. One has also to bear in mind that in the demining case, GPR data will have ultimately to be interpreted by non expert personnel. The most common GPR data visualization consists in displaying the data as a vertical slice (Line or B-scan), whilst moving the antenna along a line on the surface.

If the real size of the buried target is needed by the recognition process, pulse deconvolution and migration algorithms will be necessary to transform the target response into a more compact one. We are still looking for a robust and fast algorithm which must be able to work on cluttered images. As soil characteristics play an important role in the migration aperture, it will also be useful to develop an adaptive algorithm.

In order to distinguish an object's shape it might be necessary to display horizontal views of the ground at different depths (Area or C-scan). In this case it is necessary to combine data from several parallel scans. The distance between two parallel scans is an important parameter, in order to reconstruct the real shape of the buried object. Parallel scans are performed each 20 mm, with an acquisition each 10 mm. In order to improve the resolution we take a second set of measurements orthogonally to the first one. The area of a minimum metal AP mine of diameter 8 cm is therefore covered by about 40 A-scans.

3. Induction coil sensor imaging

Instead of converting the information given by induction coil sensors to an audio signal, as it is done in conventional metal detectors, it is possible to use it for imaging purposes (displaying a map of the metal content in the soil), and to calculate a metallic object's parameters. With respect to this approach, the ODIS project at DASA-Dornier [Borgwardt95], in cooperation with the Foerster company, has demonstrated encouraging results.

The Foerster Minex 2000SL metal detector generates two continuous wave frequencies, f1 and f2, at 2.4 kHz (for ferromagnetic objects) and 19.2 kHz (for stainless steel and alloys) respectively. To fully exploit the detector's capabilities we intercept, at the output of the receiver-transmitter module, four signals corresponding (in the complex plane) to the real and imaginary parts of the analog signals f1 and f2 induced in the receiving coils.

4. Results

The response to the minimum metal mine (containing only a striker pin of 0.1 g!), a metallic debris of about 2 g and a stone (Fig 2) have been compared (Fig 3). Results are convincing, but at time of publication, the data acquisitions have been made in the sand box only, that is in a very clean environment.

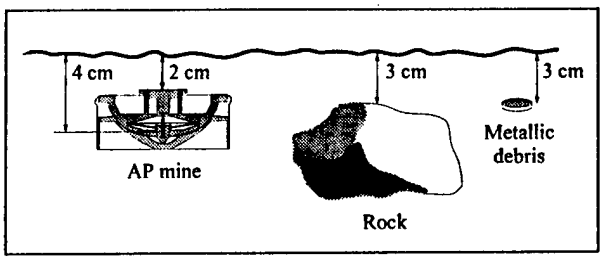


Fig 2: The 3 objects used for initial comparative tests

5. Hand-held device

Data acquisition in the sandbox benefits from the precise X-Y cartesian gantry. If the sensor is moved by hand, its position must be known precisely in order to rebuild an image comparable to the one extracted from the sand box test data. Irregular and redundant movements of the deminer must be sorted out and interpolated, in order to provide a regular

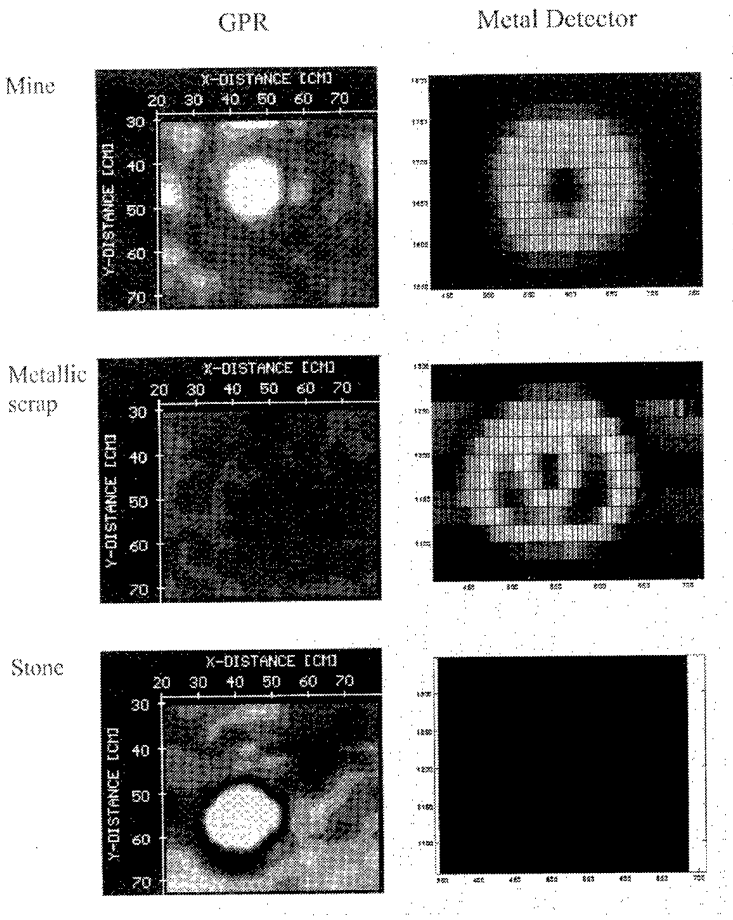


Fig 3: GPR and MD images of the three objects

x-y image. If the user is not correctly sweeping an area, he should be told to do some additional movements in a given direction.

Inertial sensors (2 accelerometers) are not acceptable, because even a slight inclination of the sensor head during the scan disturb the measure. We therefore choose to measure the distance with ultrasonic sensors (Fig 4). While the deminer is progressing within its security lane, two reflectors are moved along at each step. The area with precise enough measures (10mm) will be adjusted to 1.2m by 40cm.

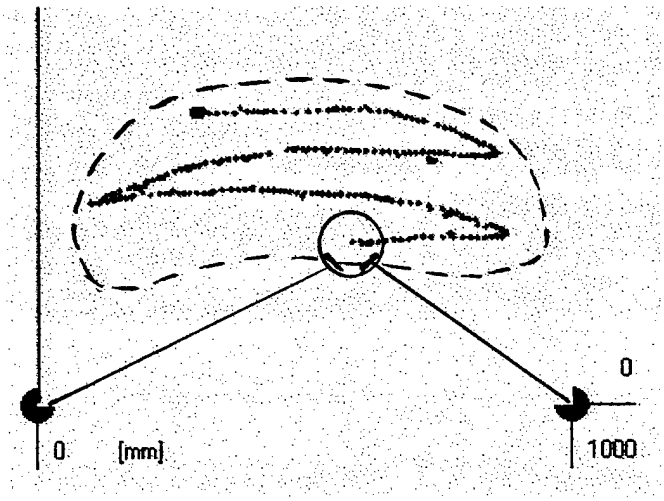


Fig 4: Area covered by the distance sensor and typical sweep movement

The metal detector and GPR antenna cannot be superposed, since the Foerster differential metal detector has a coil in its center, which disturbs the GPR antenna. We had to juxtapose these elements. The total weight is important; an integrated design will be required before any production is started.

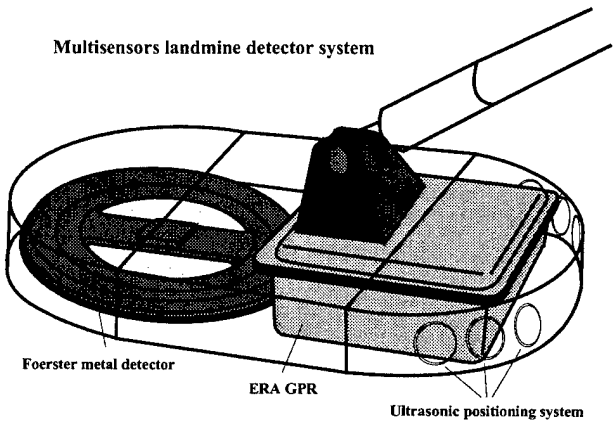


Fig 5: Proposed packaging

6. Data fusion and identification

Before talking about fusing the GPR and metal detector image, an important database should be made available, acquired in a first step in the sand box, with real mines at different depths and orientations. A signature of the image should be extracted in order to reduce the data to be compared and fused.

In a first step, it is not required to identify precisely the mine. All mines must be signalled, with a safety better than 99.6%. They may then be prodded, or destroyed immediately. False alarms must be minimized, but a factor of 2, against the current 100 to 1000, of false alarms is probably acceptable.

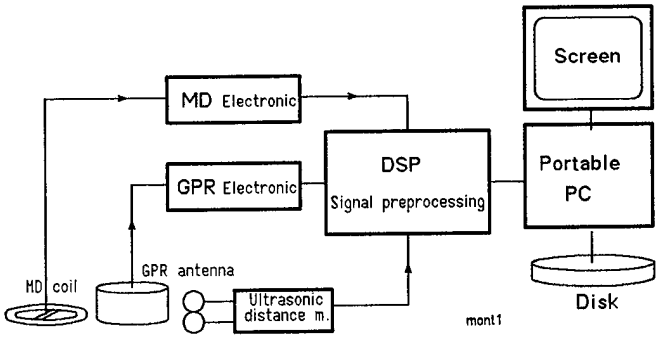


Fig 6: Block diagram of the hand-held device

The files stored during operation (about 1 Gigabyte for one day's work) have two goals. First, on the same day, the demining supervisor will be able to visualize and comment to other deminers the decisions taken for some critical cases. Sharing experience will reduce the number of false alarms, hence increasing the efficiency of the team. Second, the accumulated database will allow to later train a neural network to take by itself the decision inside a future autonomous robot. A lightweight robot like the Pemex [Nicoud96b] has the potential to explore a complete field, mark the location of mines, and allows for their simultaneous destruction. Such a solution is for the moment too expensive to be acceptable by demining organizations.

Acknowledgments

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MINE DETECTION WITH MODERN DAY METAL DETECTORS

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INTRODUCTION

With the end of the cold war, the threat of nuclear conflict has been substantially reduced. Countries around the world view this situation with both celebration and opportunity. One negative result has been an increase in regional conflicts over national and political sovereignty.

The world has seen a dramatic increase in the use of landmine warfare in many regions. Today, there is an estimated 100+ million mines which will require detection and disposal work. One reason for this increase is due to the relatively inexpensive cost of mine deployment with relationship to a highly effective strategic effect.

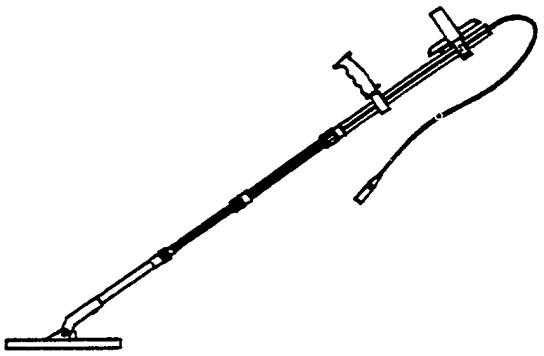
Responsible Governments are now challenged with the remediation of these mine saturated areas. In war zones this problem is compounded with the combined nuisance of OEW in the same fields.

There are a large variety of mines contaminating the planet and many contain only a very small amount of detectable metallic content. Today, manufacturers must design and produce highly reliable instruments for the detection of these mines and to insure the safety of EOD personnel. It is currently thought that approx. 99% of the placed mines contain some metal content. Therefore, modern day mine detectors with reliable technologies are very viable in meeting this remediation challenge.

APPLICATION

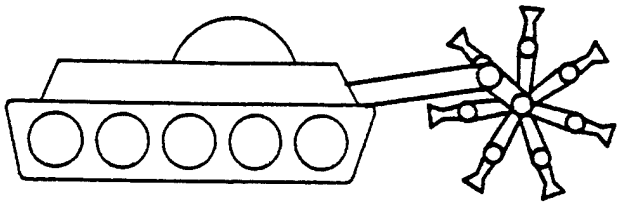
To remediate and render safe an area which is contaminated with mines, ammunition, and OEW (or the combination of these hazards), the surface must first be cleared from these explosives. This can be accomplished by two basic methods:

1. MINES: First, mines must be detected with a hand-held mine detector and immediately removed / deactivated. This work can be very fatiguing for the EOD operator and can only be done manually.



Mine clearance

So-called efficiency methods which use heavy machinery or explosives are not recommended because it cannot be ensured 100% that the mines will be destroyed. Further, a lot of metal fragments will be scattered over the area rendering it impossible to perform a repeat survey scan.

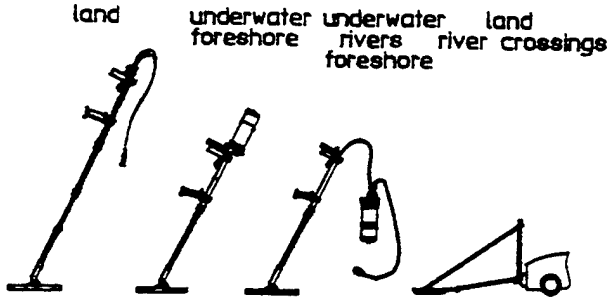


Mine breaching

2. OEW: For the detection of UXO and Explosive Waste (mines excluded), both metal detectors and magnetometers may be used together to clear surface and sub-surface targets. Advanced detection systems are available which will produce target lists and maps to assist with the removal process of these items.

DETECTOR SELECTION

For both of the above noted methods a variety of detectors are available on the market. However, only a select few models will meet the safety and detection needs for mine detection requirements.



Commercial advertisement from some companies claim detection statistics which are often only with reference to ideal level ground conditions (i.e. desert sands, roadways). Understandably, under these conditions there are several mine detectors which will produce acceptable mine detection results with little differences from one detector model to another. Unfortunately, the "real world" conditions can be overlooked by novice customers during the detector selection process.

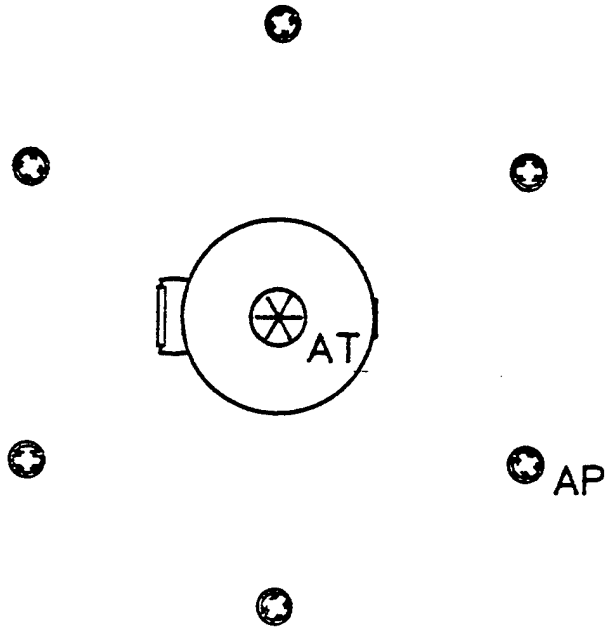
GROUND / SHALLOW WATER CONDITIONS

The following field conditions are typical considerations which are commonly encountered in mined areas:

- Searching on very uneven surfaces.
- Searching in brush, high grass, and along narrow pathways.
- Searching along embankments and cliffsides.
- Searching in muddy soil, magnetite soil, saltwater mixed soils.
- Extreme weather conditions.

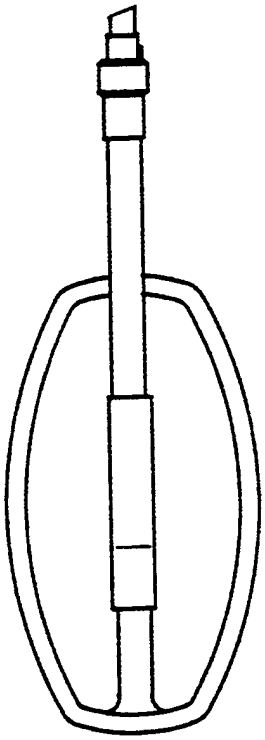
This means a metal detector (mine detector), should work to it's optimum level in all conditions to assure reliable and safe operation.

Moreover, the detection sensitivity must be very high level to detect both small metal items such as firing pins in plastic mines and larger metal targets at a greater distance below the surface. In wartime scenarios small AP mines may be placed in close proximity to larger AT mines. The detector should be able to discriminate these different targets to avoid detonation.



These requirements can only be fulfilled by a "modern day" mine detector with highly sophisticated electronics combined with an optimum physical working design. For this purpose, Vallon GmbH produces their model ML1620B along with several variations for special user requirements.

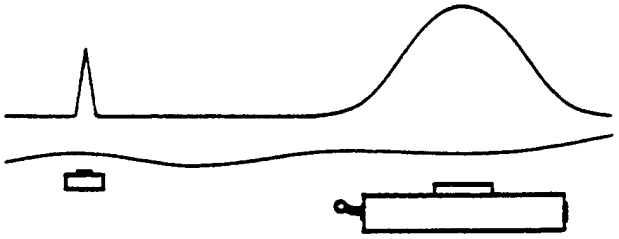
Specific details from Vallon such as their patented "Oval" search head design is highly suitable for searching under brush and near rocks, etc., and allowing the operator to maintain a necessary minimum distance between the search head and the target. Additionally, this open frame design allows a clear view of the search area for precise coverage. The lightweight design reduces operator fatigue.



TARGET RESPONSE

As the complete information of a target detection is received from the search head, a very clear and unmistakable audio alarm signal is produced by the ML1620B detector. This signal not only alerts the operator to the found target but helps pinpoint the center of the target with high accuracy.

This means that the produced audio signal must be proportional in volume and frequency to the size of the metal target and to the detection distance; the signal must not contain any other information. Interference from metal debris or other targets outside the detected target must be discriminated out or the operator will fatigue quickly and reduce the safety level of the operation.

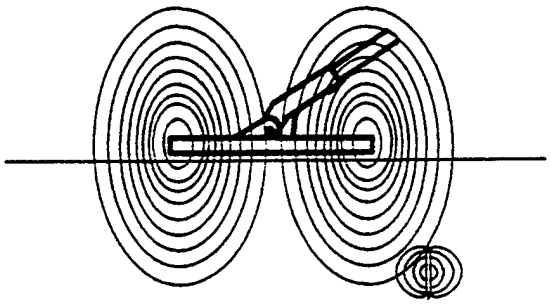


MEASURING PRINCIPLES

As already mentioned, it is estimated that approx. 99% of the ammunition and mines contain some metal content. The Vallon company has the advantage of 30 years experience in the industrial sector in the development of measuring instruments which is applied directly towards the effort of mine detection.

In principle, applied metal detection means testing the soil on specific conductivity or spots of permeability. Whereby a metallic part reacts like a linear electronic filter. This is why the metal detector consists of one or more induction coils which are controlled by an electronics unit.

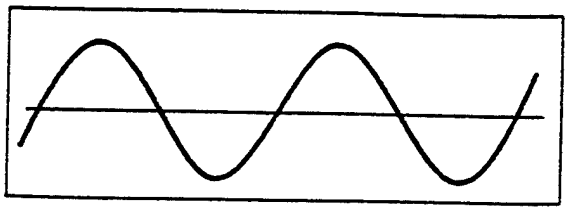
Each metal detector emits an electromagnetic field which will be influenced proportionally by the amount of electrical and magnetic conductivity within it's slope. However, not only mines or other man-made objects belong to the electromagnetic influences of the detector. Mineralized soils, water with chemical contamination, and salt water conditions produce false effects or reduce the detector's sensitivity level without the operator's awareness.



Therefore, it is absolutely necessary that the metal detector uses a measuring principle which does not produce false signal indications under the full variety of ambient conditions (the detector must also adapt instantaneously to changing ground conditions without the need for operator adjustments). For this purpose, either a single coil design (which serves as both transmitter and receiver), or a multi coil design (one transmitter coil and one or more receiver coils), may be selected.

These coils can be activated by an electronics source of either a continuous current "sinewave" or by "pulse" induction.

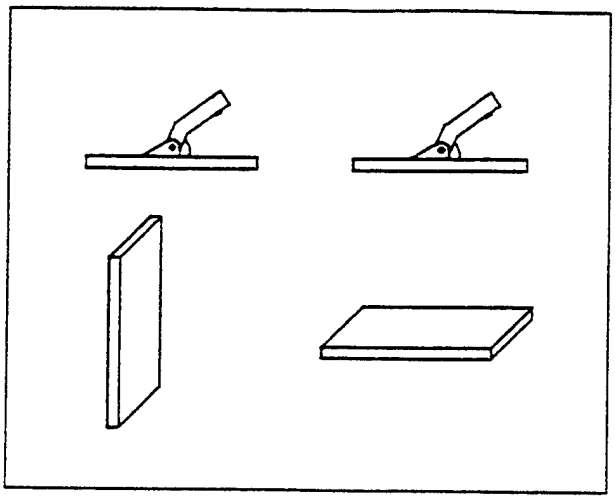
A. SINEWAVE (continuous wave), detectors emit a permanent electromagnetic field which will be influenced by magnetic or electrically conductive materials in amplitude, phase, and / or frequency.



The intensity of this influence will vary depending on the frequency (RF) applied as each type of metal must relate to an optimum frequency. This is why in the application of non-destructive testing (used by some manufacturers in the industrial sector for test documentation), the detector's operating frequency will be chosen depending on the material to be tested. Alternatively, an entire frequency range will be passed in order to obtain as much information as possible for a detector's true range.

However, experiences from this testing range cannot be directly or fully transferred to real field applications. During laboratory measurements the preparation consists of an ideal relationship between metal test samples and the detector's search coils.

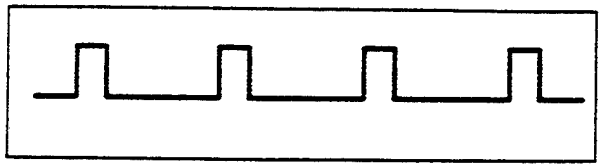
In the case of small metal targets (i.e. plastic AP mines) the metal detectors are highly and strongly influenced by the conductivity and permeability on the ground with a much smaller influence from the metal object. The metallic content, shape, and orientation of the small target will also influence the measuring results.



Only via electronic manipulations the false alarm signals from the various soil conditions are reduced to lower levels.

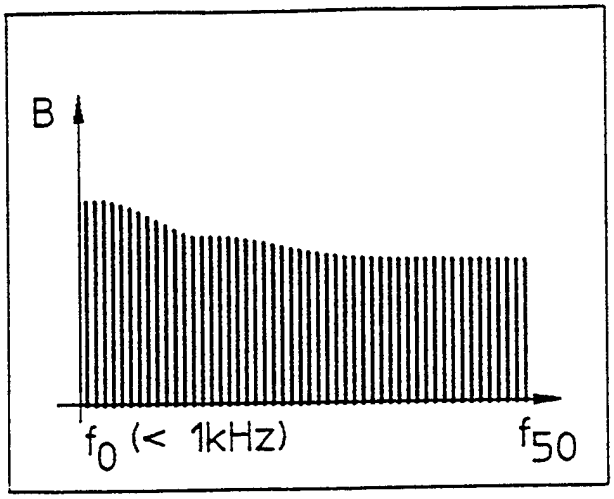
One past known hallmark of the continuous wave detector is the ability to obtain a high sensitivity detection level in soils with low electrical of magnetic conductivity. To avoid interference by ground effects in more conductive soils some manufacturers will use different coils within the same detector search head. This principle will work but is only partially effective on a very flat ground surface where the interference of the metal object is homogenous to both measuring coils.

B. PULSE INDUCTION detectors are useable in both ground searching and underwater searching applications. The ambient field conditions do not directly effect the detector's sensitivity settings. Therefore, a direct and reliable evaluation of the detector's signal is possible.

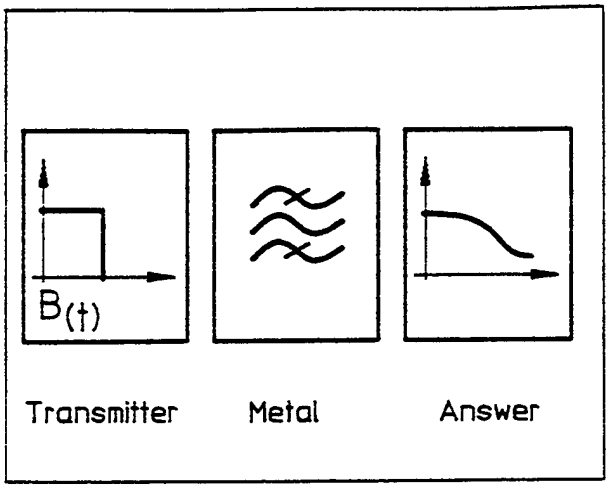


Typically the pulse detector does not achieve the same high detection sensitivity level as the continuous wave detectors. However, Vallon R & D has developed an "advanced pulse" detector which can detect equal metal targets at the same high sensitivity levels as the continuous wave detectors (without the concerns of conductive soil interference problems).

The electronically induced current impulsed through the detector coil produces an electromagnetic field which contains a high quantity of frequency points.



When this information is evaluated it corresponds with the pulse detector's many working frequencies. This allows for the use of optimum information during the process of target discrimination from ground influences.



Here, the differences in ground effect interference and a metal object is far more evident with the use of a single coil pulse detector than from multi coil arrangements. A precise signal is produces for the operator without complicated discrimination procedures.

Use of the pulse detector provides a measuring technique where digital application enhancements can be applied. Standard features include stability in all soil conditions and in all operating temperature conditions. The functions are continuously monitored and checked for 100 % reliability during use. The detectors can operate in a synchronous fashion allowing for side-by-side sweeping operations.

UNDERWATER CONDITIONS

Vallon has designed a metal detector for both underwater and land use; model MW1630 (MK29 MOD 0). As with the land version model ML1620B, this detector employs Vallon's "advanced pulse" technology.

Salt water or chemically contaminated water will not influence any operating functions. This principle also applies when using the detectors during changing soil conductivity conditions. The operator simply selects a sweeping mode and sets the desired sensitivity level. This allows for complete concentration during the searching operation. No adjustments are required making the safety level of the operation optimum for metal detector requirements (the detectors automatically adjust to changing ambient / pressure conditions without loss of sensitivity).

CONCLUSION

Mine detection in itself can be a high-risk occupation. Apart from proper training, it is essential to have mine detectors that are electronically and physically superior for the task at hand as the highest issues are safety and confidence in detection.

The proper design and understanding of mine detectors is a specialized field from which a limited number of manufacturers possess the experience and proper knowledge to fabricate top line equipment. Users of this equipment should understand the parameters of these instruments and the essential need for high quality products.

TECHNOLOGY ASSESSMENT OF PASSIVE MILLIMETER WAVE IMAGING SENSOR FOR STANDOFF AIRBORNE MINE DETECTION

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ABSTRACT - Several mine detection systems are currently under development which will provide airborne mine detection capabilities. For example, the COBRA program utilizes a multispectral video camera which will provide an interim clear weather daylight capability when deployed in a Pioneer unmanned aerial vehicle (UAV). The ASTAMIDS program has a dual approach, one contains an active polarized source as well as a passive IR camera and the other only a passive IR imager. Either ASTAMIDS system will provide day/night and limited visibility operation. The use of a PMMW Imaging sensor promises to provide day/night and all weather mine detection performance. Attenuation in the MMW regime is not dramatically effected by adverse weather. In addition there is a large contrast between metal targets and the background for air to ground scenarios. Furthermore due to the long wavelengths vegetation and soils are not completely opaque in the MMW regime, offering the possibility to detect buried targets under specific conditions. This paper will describe the assessment of an imaging PMMW sensor for mine detection. The results of data collection and modeling analysis will be presented as evidence to the utility and capabilities of the technology to perform under adverse weather conditions.

I. INTRODUCTION

This manuscript will document the feasability assessment of a PMMW system for standoff airborne minefield detection performed for the Coastal Systems Station, Dahlgran Division, Naval Surface Warfare Center under U.S. Marine Corps sponsorship. The feasability assessment consisted of a technology survey, data collection, signature analysis, and synthetic image generation. The technology survey provides an assessment of the state of the art in MMW components and imaging systems. Data was collected of mines under various conditions to demonstrate the contrast and background clutter in the MMW regime. A signature code provided insight into the effects of various parameters on the overall system's performance. Finally, a physics based image generation software package simulated the performance of an airborne PMMW mine detection system versus both visible and infrared systems.

II. PMMW TECHNOLOGY OVERVIEW

The millimeter wave regime has been exploited for both active and passive sensor systems since the 1930's. Due to the long wavelengths, MMWs are capable of penetrating clouds and to some extent rain, and are not dependent on the sun as a source of illumination. The initial use of MMW radiometers was for extraterrestrial observations. It wasn't until the 1960's, that MMW radiometers began being used for terrestrial applications. Currently, passive microwave sensors are used for meteorological, hydrological, oceanographic, and military applications. This report addresses the application of a passive millimeter wave imaging sensor to mine detection from an unmanned aerial vehicle.

A passive millimeter wave radiometer receives both thermally emitted radiance and reflected/scattered atmospheric radiance. At millimeter wavelengths the downwelling radiation or "sky shine radiance" is solely composed of atmosphericly emitted radiation. This is due to the fact that solar illumination is not scattered in the atmosphere, like it is in the visible regime. The atmosphere is highly transmissive. In general, terrestrial objects such as soil and vegetation, are highly emissive at millimeter wavelengths. They will emit radiation proportional to their

temperature, according to Rayleigh-Jeans law for blackbody radiation. Metal objects are highly reflective and highly specular, like a mirror. The radiance received from metal objects will not be indicative of their temperature, while that received from plastics and composites are a combination of transmissive, emissive and reflective. For example, mylar plastic covers are transmissive and imaging through a 1.4" gypsum garage door has been demonstrated.[1] Water and wet snow are highly absorptive, while ice and dry snow are highly transmissive. Imaging through 4.0 inches of snow has also been demonstrated in this effort and is presented in Section IV.

A. Radiometric, Apparent, or Brightness Temperature

The term used to describe the radiometric levels of an object in a scene in the millimeter wave regime is radiometric temperature (or apparent temperature or brightness temperature). This term stems from the fact that at millimeter wavelengths, blackbody radiation can be described using Rayleigh-Jeans law, which is linearly proportional to temperature. Therefore, at a given operating frequency, a temperature value in Kelvin can be used to completely describe the received radiation levels. This temperature is then termed the radiometric temperature. Because the downwelling sky radiance is at such a low level of radiance, it is termed "cold." The sky radiometric temperature is around 60 K at 94 GHz on a clear day. As the operating frequency increases and as the weather degrades the sky temperature increases. Table 1 gives typical values of radiometric sky temperature and atmospheric attenuation for various weather conditions and operating frequencies.

TABLE 1
TYPICAL MMW ATMOSPHERIC QUANTITIES.

	Operating Frequency			
Clear	35 GHz	94 GHz	140 GHz	220 GHz
Sky Temp (K)	20	40	90	120
Attenuation (dB/km)	0.1	0.4	0.9	2.5
Overcast				
Sky Temp (K)	30	105	120	190
Attenuation (dB/km)	0.2	1.0	1.5	4.0
Fog				
Sky Temp (K)	60	150	180	200
Attenuation (dB/km)	1.0	1.2	2.0	5.0
Moderate Rain				
Sky Temp (K)	75	180	220	230
Attenuation (dB/km)	1.5	1.6	2.4	5.5

B. Millimeter Wave Radiometry

The signal flow of a millimeter wave sensor system is depicted in Figure 1 below. A millimeter wave radiometer will receive, at its input aperture, both emitted and reflected radiance quantities. The aperture received radiances will also include atmospheric path radiance and atmospheric attenuation effects. Imaging in a millimeter wave system is performed either by sampling the image in the aperture plane (aperture plane imaging) or in the focal plane (focal plane imaging). A scanning lens or antenna is an example of an aperture plane imager, while a focal plane array placed behind a refractive lens is an example of a focal plane imager. A typical millimeter wave radiometer consists of a calibration source, a low noise amplifier or an intermediate frequency (IF) mixer, and IF amplifier, a detection stage and an integrator. The calibration source can also provide a gain drift compensation, will allow the calculation of radiometric temperatures from output receiver voltage levels and ensure high quality data. The sensitivity of a well designed radiometer is set by the gain and noise characteristics of the first receiver element. This makes the design of low noise amplifiers (LNAs) an important development area for the advancement of millimeter wave receivers. The use of IF mixers (super-heterodyne receivers) has historically been required due to low performance high frequency amplifiers. But, now current state-of-the-art LNAs have noise characteristics competitive with super-heterodyne receivers.

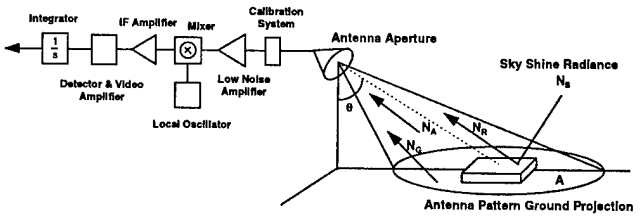


Figure 1. PMMW Radiometer System Components

C. The Millimeter Wave Advantage

The main advantage of a passive millimeter wave mine detection system is that it provides day/night, all weather capabilities. The atmospheric attenuation due to fog or rain is not detrimental to system performance, nor are the signatures dependent upon solar illumination. In addition, metal targets will provide significant contrast from the surrounding background, on the order of 200 K. Current PMMW systems are capable of better than 1 K sensitivities. Millimeter waves, due to their long wavelengths, are capable of penetrating vegetative cover and small depths of dry soil (i.e. 1-5 cm). Finally, a PMMW system will be covert in the sense that it is not emitting any radiation, such as an active system would.

The main disadvantage of a passive millimeter wave mine detection system is the poor resolution of the imagery. This can be partially alleviated by oversampling the system blur, but in general, large apertures or synthesized apertures are

required to get improved resolution. In addition the technology of MMW arrays is immature. Single element radiometers have been around since the 1930's, but it is only recently that many receivers have begun to be integrated in arrays. It is the development of monolithic millimeter-wave integrated circuits (MMIC) technology and other microfabrication techniques which has made array technologies feasible.

D. Key Issues For Application To Minefield Detection

The key issue for the development of a stand off airborne PMMW imaging minefield detection system will be defining the compromise between operating frequency, resolution, and signal to clutter ratio. In order to do reliable mine detection, at least nine pixels on target will be required, which sets the sampling criteria. Furthermore, the resolution and noise characteristics must be sufficient to provide a signal to clutter ratio resulting in a high probability of detection and a low probability of false alarm. This will require a systems engineering approach as there are many factors affecting the performance of each individual configuration.

III. State Of The Art In PMMW

The state of the art in the millimeter wave component technology and imaging system design will be addressed in this section.

A. Component Technology

There are two distinct approaches to the detection of millimeter wave radiation independent of the processing done after the signal detection. They are classical linear circuits with diode detectors or microbolometers.

The classical techniques for millimeter wave detection implies the use of RF circuit elements as shown in Figure 2. The antenna received radiation is coupled into either a front end LNA for a tuned radio frequency (TRF) detector, or the mixer which beats the received RF radiation down to an IF for amplification in a super-heterodyne detector. The amplified signal is then detected using a Schottky diode. Therefore, the required components are: a low noise amplifier, mixer, IF amplifier, and detector. Since the 1970's all the above components have been available in discrete solid state devices based on gallium arsenide (GaAs) metal semiconductor field effect transistors (MESFET).[2] Within the last five years, monolithic GaAs integrated circuits have become available for integration into fielded systems. The performance of the MESFET technology rapidly degrades above 35 GHz. Therefore, the push to high frequency operation has lead to the development of high electron mobility transistors (HEMT) and HEMT monolithic circuits. Currently, the state-of-the-art solid state RF devices are based on the pseudomorphic HEMT (PHEMT) technology, which uses a combination of InGaAs, AlGaAs and GaAs to provide enhanced electron mobility over GaAs based HEMTs.[3]

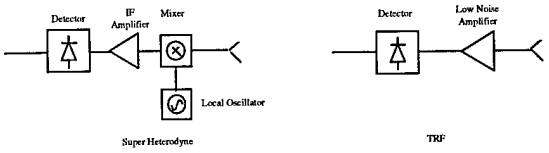


Figure 2. RF Receiver Circuit Elements.

The development of MESFET, HEMT and PHEMT monolithic integrated circuits has been pushed through the Department of Defense's Microwave/Millimeter Wave Monolithic Integrated Circuits (MMIC) Program. The objective of the MMIC Program is to develop and demonstrate the applicability, affordability, and sustained availability of MMIC technology and products through the development of chips, modules, and subsystesm for military applications. Several foundries offering HEMT capabilities include:

- Hughes
- Raytheon
- TRW
- Texas Instruments
- Lockheed Martin

Currently MMIC technology offers ICs with a fully integrated direct detection receiver.[4] The state of the art in MMIC LNA performance is given in Table 2. The immaturity of the technology and the limitations on electron mobility in PHEMTs leads to higher noise figures at higher frequencies.

TABLE 2
MMIC LNA PERFORMANCE.

FREQUENCY (GHz)	NOISE FIGURE	
	TRF (dB)	SUPERHET (dB)
35	4	3
94	5	5
140	10	7
220	15	10

The microbolometer operates by changing resistance in response to a change in temperature. The temperature change results from radiation absorption. To ensure efficient radiation absorption, the detector must be comparable in size to the wavelength of the radiation and be impedance-matched to free space. The problem with conventional microbolometers is their large thermal mass,[5] which both decreases their sensitivity and their responsivity. One

approach to reducing the thermal mass is to separate the radiation absorber and the bolometer element, which results in the antenna coupled microbolometer. Antenna coupled microbolometers have been shown to have higher responsivity, better sensitivity, and much faster response than conventional bolometers.[6] Figure 3 is an illustration of a antenna coupled bismuth microbolometer and typical readout circuitry. The key to the development of sensitive millimeter wave microbolometers is the design of small responsive load elements. The sensitivity of microbolometers is determined by three main noise sources, the shot noise, the Johnson noise, and the phonon noise. Through the choice of appropriate load element materials and dimensions, the thermal responsivity can be adjusted such that only the phonon noise is the limiting noise mechanism. Figure 4 below illustrates the noise equivalent temperature difference (NETD) of a well designed antenna coupled microbolometer as a function of operating temperature. Notice that the NETD improves as the operating temperature in decreased and as the operating frequency is increased. Through cooling of the microbolometer elements or arrays, sensitivities approaching that of MMICs can be achieved. For example a 220 GHz antenna coupled microbolometer operated at 77 K, and a 14 msec integration time has an NETD of 1.2 K.

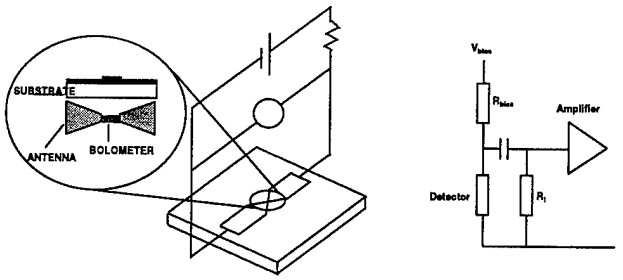


Figure 3. Antenna Coupled Microbolometer and Readout Circuitry.

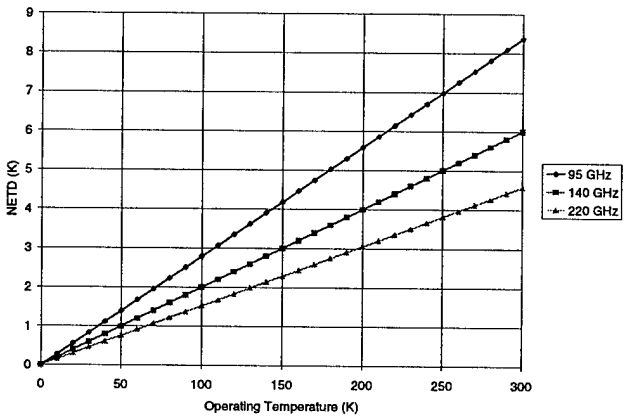


Figure 4. Antenna Coupled Microbolometer Array NETD.

Microbolometers have been successfully applied to infrared detection, and to terahertz detectors. Several sources have also demonstrated fabrication of arrays of antenna coupled microbolometers.[7,8] Millimeter wavelength microbolometers have been used for astrological observations, and plasma fusion reaction monitoring.[9]

B. Imaging Technology

There are several approaches to doing passive imaging in the MMW regime. These basic techniques are outlined in Table 3 along with advantages and disadvantages of each. Single element scanning radiometers have been in existence since the 1950's and are the most basic form of imaging system. This type of device can use conventional MMW components or the state-of-the-art MMIC receivers or microbolometers. It has been the advent of MMIC receivers, which has led to the development of linear and two dimensional arrays of MMW receivers. In general, the MMIC receivers can be one of two basic configurations: super-heterodyne or direct detection.

The interferometer type antenna can achieve the same resolution as real aperture systems with smaller elemental antennas, but the widest separation of the elemental antennas must equal the diameter of the real aperture system. The decrease in weight and convenience in placing the elemental antennas, costs signal to noise ratio and additional processing. There are two basic types of Interferometric imaging. One is the "Michelson" interferometer,[10] in which the signals received by different antennas are always added or subtracted after being transmitted to the amplifiers and processors through cables. Larger antenna separations or baselines pushed the Michelson type interferometers to limits imposed by phase distortions due to transmitting the signals from the individual antennas to the signal processors. To overcome this limitation, Brown and Twiss[10] proposed a new type of interferometer based on correlation processing, that is, time-averaging the multiplied signals. Figure 5 graphically depicts the interferometer receiver.

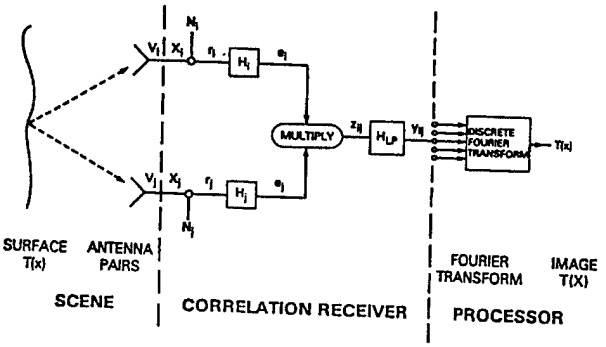


TABLE 3
PMMW IMAGING TECHNIQUES.

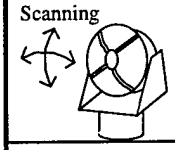
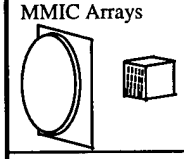
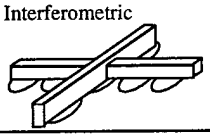
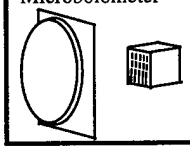
Technology	Descriptions	Advantages	Disadvantages
Scanning 	Single element scanned either in pupil plane or focal plane to generate image.	• Simple radiometer design • Well calibrated and stable • Classical, mature imaging system design	• Imaging time consuming • Mechanical design complex • Overall sensitivity reduced by number of pixel samples
MMIC Arrays 	Multiple elements configured in a focal plane imaging system, where each element represents a single MMIC receiver.	• Starring image acquisition • Best possible integration times	• Difficult to calibrate • High power consumption • High cost • Above two limits number of possible pixel elements
Interferometric 	Use of sparsely placed multiple receivers or slot antennas and coherent processing to synthesize an aperture larger than any single receiver element.	• Improved spatial resolution • No moving parts	• Significantly reduced sensitivity • Tight tolerances on antenna spacing and design
Antenna Coupled Microbolometer 	MMW antenna coupled to a thermo resistive load fabricated on a substrate with many antenna coupled elements.	• Starring image acquisition • Dense array of pixel elements • Cheap batch processing • Low power	• Reduced sensitivity

Figure 5. Imaging Interferometer Processing.[12]

Since the correlation interferometer was originally developed for radio astronomy, the theory incorporated assumptions valid for this application. The next application, because of the potential to achieve higher resolution without the mass of larger apertures, appears to have been space to ground imaging using microwaves. As the range decreases, the validity of basic assumptions must be reviewed, particularly for mine detection. For example, the assumption that the waves are planar and not spherical needs to be reviewed. However, current work in overcoming the need to make this assumption is being done by Soumekh.[11]

As shown by Ruf, et al,[12] for the same integration time, the noise equivalent temperature of an array is always greater than that of a single receiver with the same system temperature and bandwidth. However, the integration time afforded by the array is greater since the integration time can be the frame time required by the scanning antenna to scan the same scene. In the case of the focal plane array (FPA) imagers, the integration times would be equivalent. Additional reduction in the noise floor can be achieved by the equivalent of time-delay and integration (TDI) used in IR systems since the signals from the antennas can be stored.[13] This requires that the positioning of the array be accurate enough to allow the TDI to be effective.

Passive array imaging is also known as Fourier synthesis array imaging, since the output of the correlators are proportional to the Fourier transform of the intensity of the scene at a frequency dependent on the spacing between elements.[14,13] Usually, the array is laid out on a rectangular grid with uniform spacing. The spacing between elements is usually half a wavelength but spacings up to about a wavelength have been considered. A filled array is one with an elemental antenna at each grid point. However, only one antenna pair is required for each grid spacing, or all multiples of half wavelengths covering the desired aperture (minimally redundant).[13] For a filled array, the redundant pairings are used to decrease the effective temperature noise. Algorithms for determining minimally redundant arrays are brute force algorithms which require long computation times on large computers.

Since image reconstruction requires reconstruction from the Fourier components of the image, one can presume that the relative spacings of the elemental antennas must be well known. Good[15] shows that severe problems can arise if there are uncertainties in the positions of the interferometer elements. For normally distributed spatial errors which are uncorrelated between antenna elements, the effect is similar to that of the same type of phase errors in optical telescopes.

There are several system developments of interest which are currently underway. Eglin Air Force Base (AFB) under

the Smart Tactical Autonomous Guidance (STAG) program, is developing several radiometers and imaging concepts. One of these devices is the Millimeter Wave Analysis of Passive Signatures (MAPS) trailer. The MAPS is under development by Millitech Corporation in South Deerfield, MA. The MAPS consist of four radiometers and a video camera mounted on a trailer. The data collection and radiometers are controlled from inside the trailer. The National Institute of Justice is sponsoring the development of an 8x8 MMIC based focal plane array, which is being developed by Millitech Corporation.[16] This device will be capable of imaging 30 frames per second with ~2 K temperature sensitivities. The 8x8 array is dithered to get a 32x32 pixel image. A super resolution algorithm is applied to the images that provides a 4 times improvement in the resolution. TRW, under the DARPA Technology Reinvestment Program (TRP), is developing an 40x26 MMIC based focal plane array.[17] This device will provide imagery at a 17 Hz frame rate with ~2 K temperature sensitivity. A conceptual drawing is given in Figure 6.

The Army Research Laboratory has sponsored ThermoTrex's development of a real-time imaging radiometer based upon interferometric imaging techniques.[18] Figure 7 illustrates the ThermoTrex design, which uses a Bragg cell to perform the required correlations and image reconstruction processing in real-time. The current system is capable of only 20 K sensitivities, with developments underway to improve the performance. The University of Massachusetts under sponsorship of NASA Langley, has developed the Electronically Scanned Thinned Array Radiometer (ESTAR).[19] This system operates at 1.4 GHz and is a reduced redundancy interferometric imaging array in one dimension and a real aperture imager in the other dimension. It is typically flown on a P3 for terrestrial remote sensing. The ESTAR is illustrated in Figure 8 below.

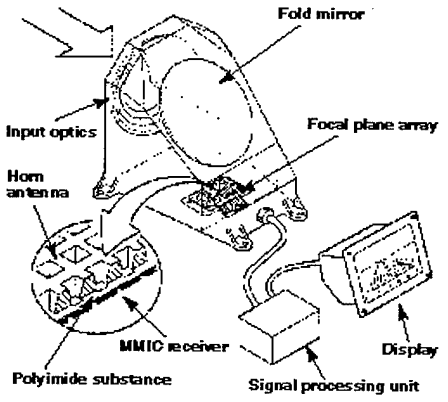


Figure 6. TRW MMIC Based FPA.[17]

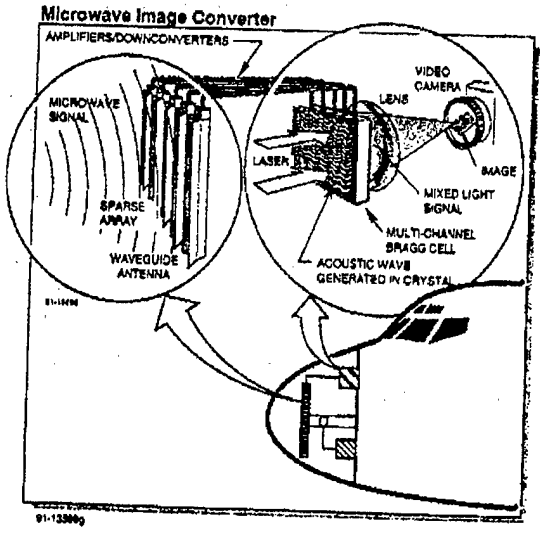


Figure 7. ThermoTrex Real-Time PMMW Imager.[18]

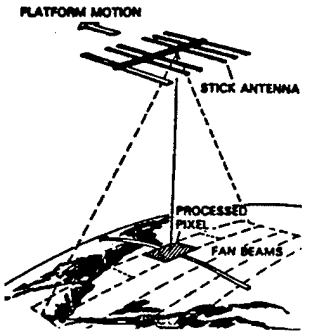


Figure 8. UMass ESTAR System.[13]

IV. Feasibility Assessment

The feasibility of using a PMMW imaging sensor for stand off mine detection has been established through data collection, system performance evaluations, and synthetic image generation. The data collection took advantage of the Air Force developed Millitech radiometer. Data was collected of mines against an ice/soil background and under snow. The system performance model quickly evaluated various weather conditions and system configurations. Finally, synthetic imagery was used to demonstrate the performance of a PMMW imager flown from a UAV, and to compare that performance with similar visible and IR systems.

The Millitech radiometer was capable of sensitivities better than 0.01 K. This device was designed for performing phenomenology investigations.[1] The data collection took place in January 1996. A diagram of the test set up is given in Figure 9. An example of the data is shown in Figure 10.

The metal plates are oriented such that the coldest part of the sky (i.e. zero degrees zenith) is reflected off the plates into the radiometer. The inert mines are laid flat on the ice and are reflecting a warmer part of the sky than the metal plates. Therefore, the contrast between the mines and background is reduced. In an operational scenario, the mines would have contrast similar to the metal plates. In Figure 11, the entire test set up is under 4.0" of new snow. There is no difference between the data with snow cover than without snow cover. This demonstrates the penetration capabilities of PMMW imaging sensors. Notice that the plastic and the fiberglass mines are both observed as warmer than the background. This is as the theory predicts.

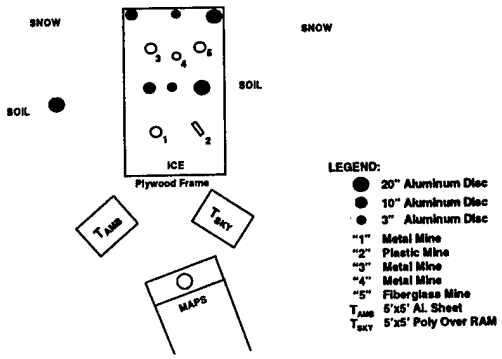


Figure 9. Data Collection Test Set Up.



Figure 10. PMMW Imagery Of Mines.

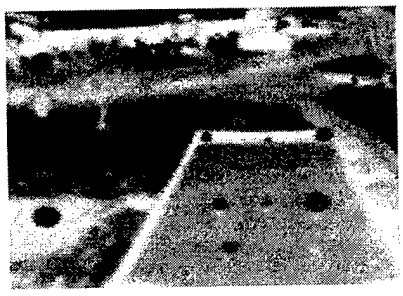


Figure 11. PMMW Imagery Of Mines Under 4.0" Of Snow.

The data collection demonstrated the capabilities to image mines at 94 GHz under clear conditions. But would a PMMW radiometer have similar performance under adverse weather conditions? A system performance model was developed by NRC to address this question and execute performance trade off analyses. Figure 12 below depicts the performance of several PMMW system configurations. The system configuration assumed capabilities compatible with current detectors used in a scanning mode and operating at an altitude of 300 feet. As the operating frequency of a PMMW radiometer is increased, the atmospheric attenuation is increased as well as the sky temperature. This decreases the contrast between a metal mine and the surrounding background, thus decreasing the signal to clutter ratio. As the operating frequency increases, the resolution of the system improves, resulting in more of the target filling an image pixel. This will provide improved signal to clutter ratios under conditions where the target is smaller than the pixel's ground projection. From analysis of Figure 12, it can be seen that the effect of improved resolution can provide enough signal to overcome the reduction in contrast. The size of possible apertures for a UAV are between 0.3 and 0.5 meters. For an aperture of 0.4 meters, the best overall performance is provided by a 94 GHz. It is also important to notice the signal to clutter ratios can be directly related to the performance of a mine detection algorithm. These results indicate improved performance through the use of a PMMW mine detection system.

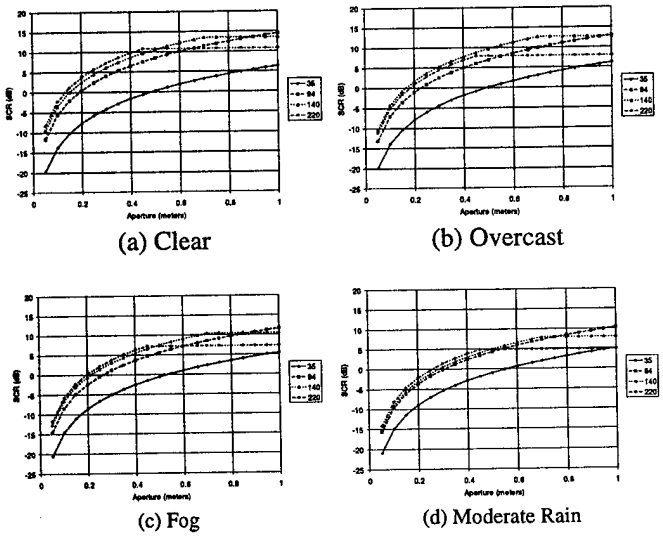
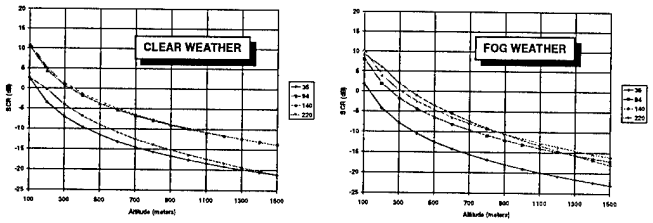


Figure 12. PMMW Imagers Performance Versus Input Aperture and Weather.

Plots of the signal to clutter ratio versus the operating altitude for an aperture of 26 inches are shown in Figure 13. Figure 13a assumes a scanning radiometer, while 13b

assumes a starring focal plane array radiometer under fog conditions. These two cases illustrate some interesting points. One is that the 220 GHz system suffers from poor performance under short integration times, which is due to the larger noise figure. If the integration time is increased to drive the sensitivity well below the clutter, the fill factor dominates the system performance as evidenced by the improved performance of the 220 GHz system in Figure 13b. As the altitude continues to increase, the atmospheric effects versus frequency begin to dominate the system performance. It can be seen in Figure 13b that the 140 and 94 GHz system performance surpasses the 220 GHz at 900 and 1200 meters altitude respectively.



(a) 0.1 msec integration (b) 14 msec integration

Figure 13. PMMW Imagers Performance Versus Altitude.

Finally, synthetic imagery was generated of a modeled deployed PMMW imager on a UAV. This was compared with similarly configured modeled visible and IR imagers. Furthermore, the comparison was made for clear day, fog, and night environmental conditions. These results are depicted in Figures 14 through 16. The failure of the visible imager to produce usable imagery under night and fog conditions is obvious. Under clear conditions neither the visible nor the infrared, provided near the contrast of the PMMW imager. This clearly demonstrates the improved and all weather capabilities of a PMMW mine detection system. The imagery was generated using the Irma 4.0 software developed by NRC for Eglin AFB[20].

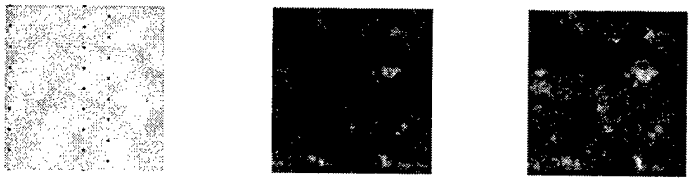


Figure 14. PMMW, IR, Visible Imagery Of Minefield From UAV Under Clear Weather Conditions.

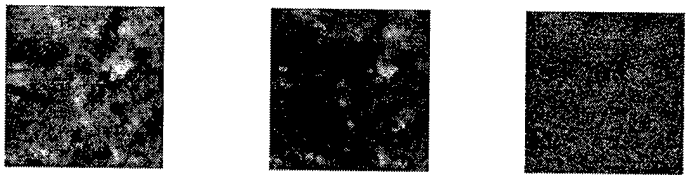


Figure 15. PMMW, IR, Visible Imagery Of Minefield From UAV Under Fog Weather Conditions.

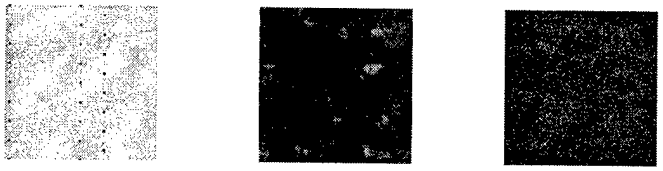


Figure 16. PMMW, IR, Visible Imagery Of Minefield From UAV Under Clear Night Weather Conditions.

C. Buried Object Detection

The capabilities of millimeter waves to penetrate soil, vegetation and other materials has already been alluded to. The skin depth (or penetration capabilities) of materials is a function of frequency, as illustrated in Figure 17 below. As the frequency increases, the skin depth decreases. The skin depth of soil is a strong function of soil moisture content. This is why millimeter wave or microwave sensors are often used to measure the soil moisture content. Figure 18 depicts the skin depth of a sandy soil at 35 GHz as a function of soil moisture content.. From Figures 17 and 18 it should be clear that for buried object detection, a lower operating frequency is desired. However, for stand off distance and better spatial resolution, a higher operating frequency is desired. Using models developed by NRC, the temperature difference or contrast, for a metal mine under a sandy soil with various moisture contents has been evaluated versus burial depth. These results are given in Figure 19. At 94 GHz, under dry soil conditions, a PMMW sensor would be able to detect an object buried less than 1 cm. While for the same conditions a 35 GHz system would be able to detect a buried metal object greater than 20 cm. Although under wet soil conditions a 35 GHz radiometer would be limited to under 1 cm. A clear improvement in buried object detection results by operating at 1.4 GHz. Even under wet conditions metal objects buried up to 10 cm would be detectable. Several people have demonstrated a PMMW sensor's ability to detect buried objects.[21,22]

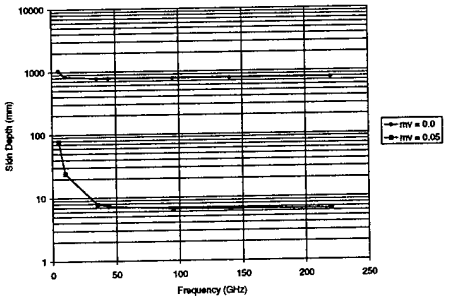


Figure 17. Skin Depth Versus Operating Frequency Of Sandy Soil At Two Different Soil Moisture Contents.

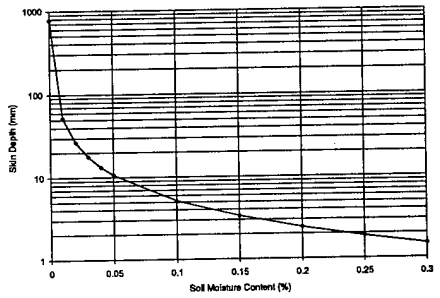
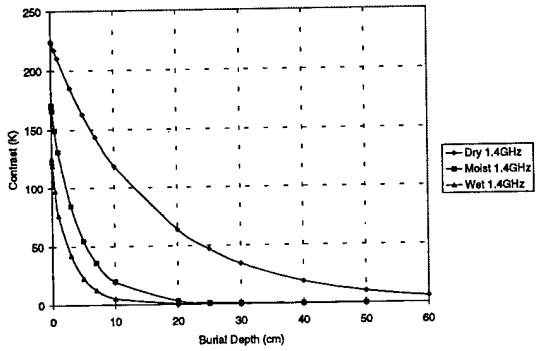


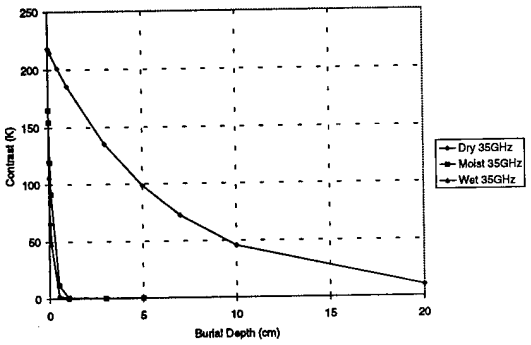
Figure 18. Skin Depth Versus Soil Moisture Content For Sandy Soil At 35 GHz.

In the case of buried plastic mines, the material properties of the soil and mine are closely matched. This makes plastic mine detection much more difficult. In this case, by increasing the soil moisture, the contrast between the mine and the soil is increased at and just below the surface. The increased soil moisture, also increases the attenuation within the soil, which will quickly overcome the initial increase in contrast. Figure 20 illustrates the temperature difference between a buried plastic mine and a sandy soil background with various moisture contents. The inset in Figure 20c illustrates the improved contrast of the plastic mine versus the wet background and the quick attenuation of the signal versus the burial depth.

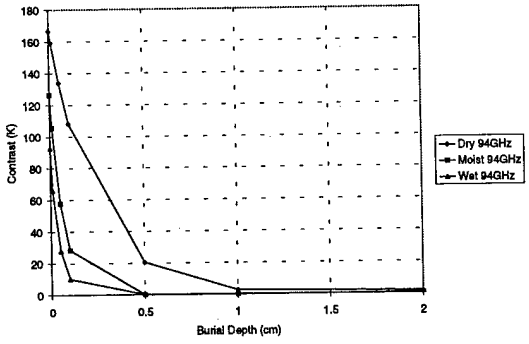
In conclusion, buried mine detection is a difficult problem, dependent upon several parameters: soil type, soil moisture, mine type, burial depth, and operating frequency. Characterization of this problem requires a system level analysis, dedicated to evaluating the sensitivity of buried mine detection to each of these parameters. The main objective of the current analysis was to assess the capabilities of a PMMW sensor to provide stand off airborne mine detection. This objective imposes system requirements which are not conducive to buried mine detection, such as a



(a) 1.4 GHz



(b) 35 GHz



(c) 94 GHz

Figure 19. Contrast Of Buried Metal Mines In Sandy Soil.

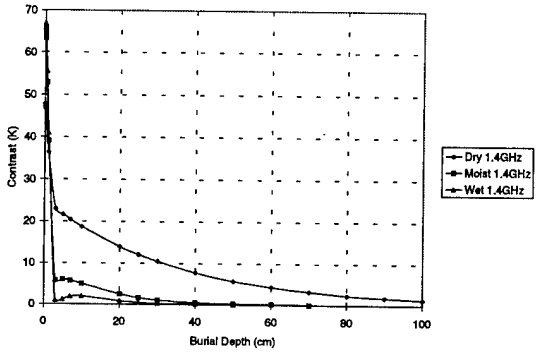
required operating frequency between 94 and 220 GHz. This operating frequency range is required to achieve sufficient resolution for mine detection at altitudes greater than 300 feet above ground level.

D. Plastic/Wood mine detection

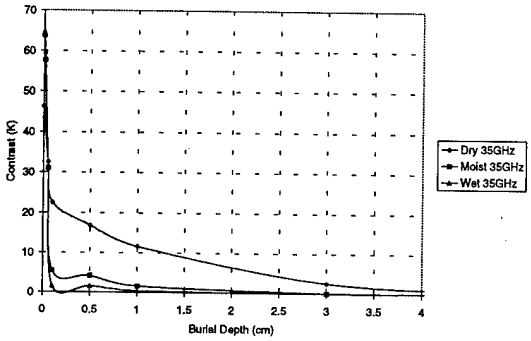
Plastic and wood mines are both highly emissive and will appear warmer than the background. Sample contrast temperatures of plastic and wood mines versus soil backgrounds are given in Table 4. As already mentioned, it is interesting to note that as the soil moisture increases, the contrast improves. This is due to the increased water content decreasing the soil's emissivity.

TABLE 4
PLASTIC MINE CONTRAST VERSUS SOIL BACKGROUND.

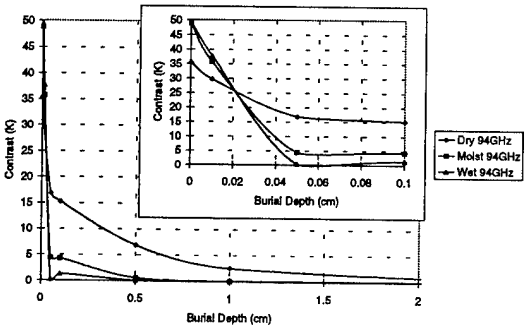
		CLEAR WEATHER CONTRAST		OVERCAST WEATHER CONTRAST	
TARGET	FREQ (GHz)	DRY	WET	DRY	WET
Plastic	94	5.80	61.00	4.18	44.19
	140	4.50	48.00	3.80	40.00
	220	3.80	40.00	2.06	21.80
Wood	94	10.60	66.00	56.00	16.20
	140	8.38	51.00	51.20	14.78
	220	7.01	43.00	27.70	8.02



(a) 1.4 GHz



(b) 35 GHz



(c) 94 GHz

Figure 20. Contrast Of Buried Plastic Mines In Sandy Soil.

E. Effects of Water

It is well known that MMWs do not penetrate water. This makes water a strong mix between being reflective and emissive. Figure 21 gives the skin depth of water as a function of operating frequency. As can be seen, the higher the operating frequency the more susceptible a PMMW system is to the effects of water. Table 5 contains examples of the expected temperature contrast of metal and plastic mines with a thin layer of water (i.e. 1 mm) against a saturated soil background.

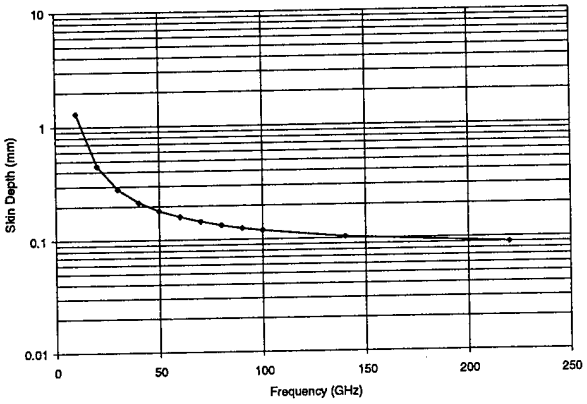


Figure 21. Skin Depth of Water Versus Operating Frequency.

TABLE 5
CONTRAST OF WET METAL AND PLASTIC MINES AGAINST SOIL.

		CLEAR WEATHER CONTRAST		OVERCAST WEATHER CONTRAST	
TARGET	FREQ (GHz)	DRY	WET	DRY	WET
Wet Metal	94	78.00	22.00	31.14	8.80
	140	61.00	17.68	38.35	8.08
	220	51.00	14.00	15.38	4.38
Wet Plastic	94	43.00	12.30	7.70	47.70
	140	33.00	9.60	7.01	43.45
	220	28.00	8.08	3.80	23.00

V. FEASIBILITY ASSESSMENT CONCLUSIONS

The feasibility of using a PMMW imaging sensor for stand off airborne mine detection has been demonstrated through data collection, signature analysis and synthetic image generation. The data collection activities demonstrated the high contrast between metal objects and the surrounding background. The data collection activities also demonstrated the capabilities of PMMWs to detect objects not detectable by other sensors, such as objects buried under 4.0" of snow. The signature modeling results indicated a target to background signal to clutter ratio of up to 7.5 dB under severe fog conditions. Finally, the synthetic imagery has demonstrated the advantage that passive millimeter wave systems have over infrared and visible systems under adverse weather conditions and during either day or night operations. From the analysis, it has become apparent that a real aperture 35 GHz system will be incapable of meeting the system requirements due to the poor resolution. It also has become apparent that the choice of operating frequency will be highly dependent upon the choice of operating altitude and antenna aperture diameter.

A PMMW system will lend its self well to the detection of buried objects, but not from an airborne platform. The apertures required to get only target pixel information at the soil penetrating frequencies are prohibitive. The detection of plastic, wood and metal mines is feasible. The plastic and wood mines will be warmer than the background, and the metal mines will be much cooler than the background. The design of a buried mine detection system will require a systems engineering approach, as there are many variables which affect the performance of a PMMW buried mine detection system.

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DARPA'S HYPERSPECTRAL MINE DETECTION PROGRAM

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ABSTRACT–The DARPA sponsored Hyperspectral Mine Detection (HMD) program is investigating, developing, and demonstrating a hyperspectral infrared capability for remote buried mine detection. The primary hyperspectral infrared phenomena that is being addressed is a spectral signature due to soil/sub-soil differences, allowing infrared detection of buried mines via the disturbed soil. Since late 1994, the program has collected extensive non-imaging and imaging data of buried mines and mine surrogates in the 0.4 to 14 micrometer wavelength region. The data has been used to develop algorithms that have discriminated between undisturbed and disturbed soils, indicative of a buried mine. Data has been taken over a wide range of soil types and locations to better define the utility of this technique. Test results indicate that disturbances can be detected from days to months later, even after severe weathering has removed all visible clues. In parallel with the phenomenology and data processing investigations, HMD is developing a hyperspectral, imaging spectrometer operating in the 8-12 micrometer region, suitable for airborne detection of buried mines. The completed sensor and all associated data processing hardware will be integrated into a helicopter in late 1996. The following series of performance verification flight tests will culminate in a demonstration of remote buried mine detection in early 1997. In this paper, relevant results from the phenomenology, data processing, sensor development, and field testing portions of HMD are summarized.

1.0 Introduction

The DARPA sponsored Hyperspectral Mine Detection (HMD) program was initiated in FY 1994 to investigate methods for remote detection of buried land mines using advanced hyperspectral sensors. The technology of hyperspectral sensors is rapidly advancing and has recently been extended into the reflection and thermal infrared. Airborne hyperspectral sensors have already demonstrated new levels of target detection of targets (including mines) on the surface. The HMD program is concentrating on extending this surface detection capability to the situation of buried mines. Buried mines are a highly effective military and terrorist weapon, since the mines are inexpensive, extremely difficult to counter and can be placed with comparatively little risk. While they are easy to lay, they are very difficult to detect, accurately locate and remove or destroy. Land mines pose a significant threat to U.S. forces and inhibit the safe movement of soldiers and equipment. Countermining technology currently employed varies widely in both approach and type of equipment used. All techniques are manpower intensive and dangerous and no technology has been deployed that will allow the standoff detection and/or

standoff neutralization of all the mines in a mine field. The DARPA Hyperspectral Mine Detection program is identifying and developing technology to find mines quickly and affordably. Hyperspectral Mine Detection sensors can be employed from a helicopter or a low flying aircraft to detect mines on roads and in off-road areas. The output of the HMD sensors will be a map of the positions of individual mines along the road or in the off-road area.

2.0 Phenomena

The DARPA Hyperspectral Mine Detection program has made measurements over the full optical spectral region from visible through long wave infrared. Every effort was made to explore all possible observables and specific sensors were deployed to cover each spectral region. The emphasis of this program has been on detection concepts using midwave infrared (3-5 um) and longwave infrared (8-12 μm) because of observed long persisting phenomena in these spectral regions.

The principal phenomena identified for hyperspectral mine detection is based upon detecting localized differences in the scene created by the mines. The placement or presence of the buried mine will change the observables of a small area above the mine. Initially, this observable may be simple to detect by other techniques. For example, immediately after placement there will likely be a texture or moisture difference that can be detected with a broad band infrared instrument or even visible light sensors. Shortly, after drying and weathering, the obvious texture and moisture differences may disappear. What remains as an observable are long term effects of the soil disturbance.

The hyperspectral mine detection concept is based upon the existence of some compositional or particle size difference between the soil above the mine and the surrounding area. This difference will result in a localized difference in the spectral signature of the surface of the soil that can be observed by a hyperspectral or multi-spectral sensor. It is also possible that the existence of the mine itself can be an observable since it can introduce localized differences in the temperature of the surface and in the behavior of vegetation growth in the near surface area.

The disturbed surface phenomenology and possible buried mine observables were investigated for the infrared and reflection band spectral regions. All soils show some spectral structure in the 3-5 μm and 8-12 μm regions. These spectral features are characteristic of the soil mineral content. The surface layer can be different from the subsoil either because of compositional differences or because of particle size differences. Many laboratory measurements in the long wave infrared have shown that the particle size is an important determinant of the magnitude or strength of the spectral signature[1]. Very small particles (comparable in size to the wavelength of the infrared radiation) generally exhibit less spectral variation (the spectral signature or color) than larger particles of the same mineral. Thus, even for soil where there is no compositional difference between the top layer and the subsoil, the different sorting of sizes will result in a different spectral signature.

There are also spectral differences between disturbed and undisturbed soil in the visible and short-wave infrared region. In particular, wet soil has an overall reflectance difference from dry soil. Thus, a fresh mine can be immediately detected with a visible light sensor (or human eye) in many cases because the subsoil now over the mine is wetter than the surrounding areas. The disturbed soil will appear darker than the surrounding undisturbed soil. This difference will only last until the water evaporates or a rain shower wets everything. Other potential spectral differences in the short-wave infrared can arise from soil clay content but have been determined to be unreliable. Also, the spectral region around 2.2 μm is a region where the signature of the moisture content of soil is particularly strong. This particular signature may last longer than the broad reflection difference due to wet soil. It will not last as long as the signature due to a true compositional or particle size difference.

3.0 Sensor Experiments

Hyperspectral data were acquired over many regions of the United States using both non-imaging and imaging spectrometers. Three major imaging sensor deployments were conducted using both a mid-wave infrared imaging spectrometer and a long wave infrared imaging spectrometer. During these imaging deployments large data sets on disturbed and undisturbed soil and on buried mines were acquired. The imaging data sets were used extensively to study the phenomena and develop detection techniques. These large imaging data collections were supplemented by many geologically and geographically dispersed non-imaging collections. By referring to Figure 1, the broad base of the measurement program can be seen. Data has been taken in the Desert Southwest, the Eastern Seaboard and in the Hawaiian Islands. Special emphasis was made to acquire a wide variety of geologically different soil types using field teams with trained geologists. For the vast majority of these locations, the same spectral observable was found in the long wave infrared. In most of the remaining locations, a secondary spectral observable in the long wave infrared, useful for detection, was found.

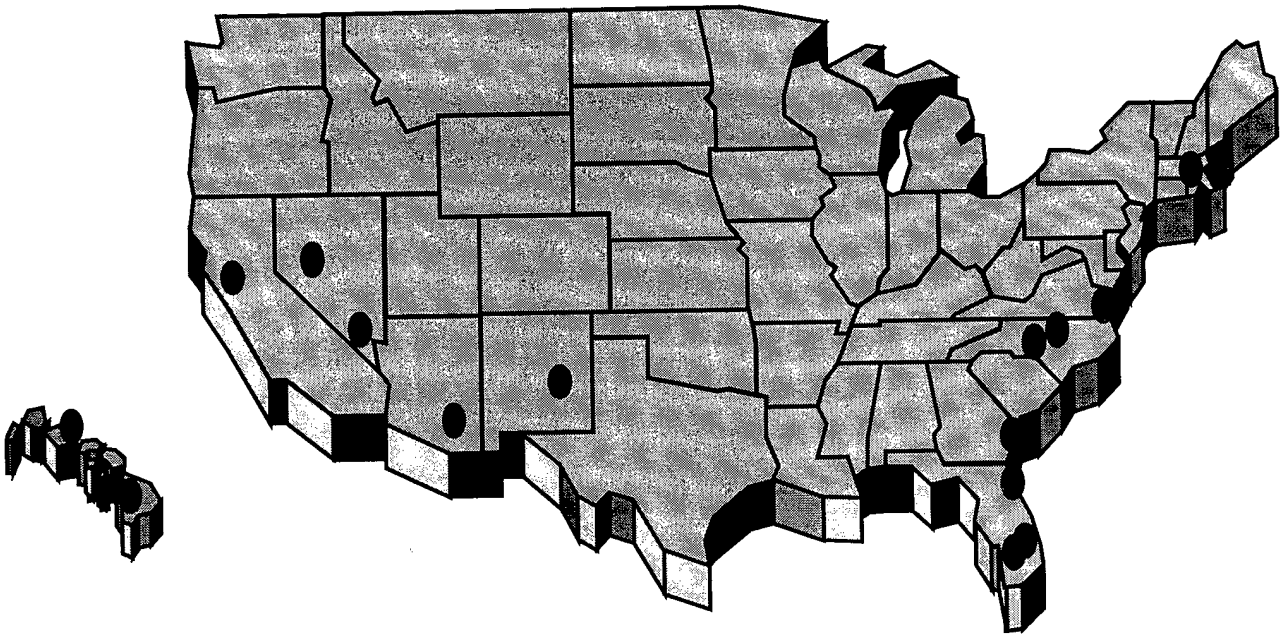


Figure 1. Map of the United States Showing Locations Where HMD Experiments Have been Performed. Imaging experiments have been performed in Southwest (Arizona and Nevada), while non-imaging experiments have been performed in Hawaii, California, New Mexico and along the Eastern Seaboard

The major spectral observable in the long wave infrared is due to the silicate reststrahlen feature at 9.2 μm. This feature is seen in both disturbed and undisturbed soil. There is no real spectral difference between the disturbed and undisturbed soil; only the magnitude of the signature varies. Undisturbed soil almost universally shows a much stronger reflectance (lower emissivity) at the spectral location of the silicate reststrahlen feature. In some cases, the effective emissivity difference between disturbed and undisturbed soil has been measured to be greater than 10% in the 9.2 μm band.(see figure 2)

The explanation for this difference is that there is a particle size sorting of the dirt in a natural soil environment. Weathering on the top layer tends to remove small particles (of 10 to 50 μm in size) from the surface. When a mine is buried, soil from below the surface is placed on the surface and this new soil contains a mix of small particles and large particles. The spectral signature is then reduced because the spectral signature of small particles is much lower than the spectral signature of the larger particles which normally reside on the surface.

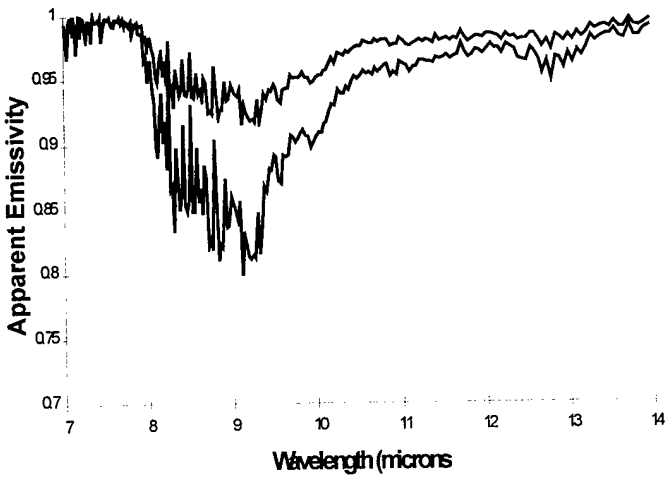


Figure 2. Field measured emissivity on the same soil showing a signature difference at 9.2 μm between the surface soil (the bottom curve) and the subsoil brought to the surface by digging (the upper curve).

During the course of the HMD Measurements program, other observables for mine detection have been measured. In particular at some of the locations a compositional difference has been seen between the surface layer and the subsurface layer. This compositional difference can be caused by rocks or vegetation differences in the area. Measurements were also made on silicate free soils at locations in Hawaii.

Imaging spectrometer measurements proved to be essential to the understanding of the phenomena behind mine detection. Not only do imaging measurements give orders of magnitude more data than non-imaging measurements, but they provide data to support the understanding of the spatial aspects of the mine signature.

An example from the imaging data collections is included here. This data was acquired using the Lawrence Livermore National Laboratory LIFTIRS hyperspectral LWIR Sensor [2]. A further discussion of the sensors and experiment may be found in [3}.

The example in Figure 3 shows the application of a detection algorithm to the problem of detecting mines buried in a road. This data was taken from a range of approximately 1100 feet with the sensor on a cliff side location. Broad band infrared data is shown first, with the road running through the center. No mines are apparent in this broad band image. The second image shows a composite color image made from the first three Principal Components. The mines can be seen as patches along the side of the road. The mines could be detected with a spectral matched filter if the off-road area were excluded from consideration. Since it is the aim of the HMD program to detect targets both on the road and in the off-road area, a quadratic detector was then applied to the data. This detector, using training information from one mine, was able to detect all the mines and reject false alarms not only on the road but in the off-road area.

4.0 Sensor Development

As part of the DARPA HMD program, a new hyperspectral long wave infrared imaging sensor is being developed by the University of Hawaii. This sensor, the Airborne Hyperspectral Imager (AHI) will fly on a helicopter platform and be used for mine detection experiments in 1997.

The AHI sensor is a grating spectrometer and is designed to operate from an airborne platform. AHI will acquire spectra for a row of 256 pixels on the ground simultaneously and build up the second spatial dimension by pushbroom scanning . A HgCdTe 256 x 256 longwave infrared imaging array is used as the focal plane and is cooled to liquid nitrogen temperatures.

The AHI sensor will be installed into a helicopter platform and will acquire hyperspectral data from an altitude of 100 meters. From this altitude, a mine will be seen on multiple sensor pixels. The output of the sensor will be digitized and calibrated in real time on-board the helicopter. The calibrated data will be presented to the operator in real time.

In addition, mine detection processing will be performed in real time on-board the helicopter. The mine detections will be geo-referenced using a Global Positioning System receiver. All calibrated data will be recorded and will be available for further processing at the ground station.

5.0 Summary

The disturbed soil signature due to the placement of a buried mine can be seen as a spectral difference from the neighboring undisturbed area. While the strength of this signature is strongest immediately after mine emplacement, it will remain strong for a period of days to weeks and is difficult to suppress. Experiments have shown the mine detection observable to be detectable after a period of weeks to months depending on the degree of weathering. Since the weathering process is what sorts the small particles from the large particles and creates the observable, large amounts of rainfall will tend to wash the small particles from the surface layer. Nevertheless, disturbed soil signatures have been measured after months of weathering, including rainstorms. A residual disturbed soil signature has also been seen in mine fields that had been flooded.

The detection of buried land mines by the signature of the disturbed soil has limitations. It cannot be used, in general, for the detection of long buried mines. There are other observables that may be applicable to the detection of mines buried for long periods of time (from several months to years). Preliminary results show that the long buried mines can be seen at certain times of the day as a thermal anomaly. Immediately after sunrise, the thermal mass of the mine retards the solar heating of the soil above the mine. At least in the sparsely vegetated desert areas where these experiments were conducted, there was a distinct lack of vegetation over the mine due to the restrictions in root growth. Mines buried over two years were used for these experiments. The coupling of a vegetative anomaly (lack of vegetation) and a temperature anomaly could be a good indicator of a long buried mine.

6.0 Acknowledgments

The authors wish to acknowledge the support of the Defense Advanced Research Projects Agency (DARPA), NCCOSC/NRaD, and the personnel of Fort Huachuca, AZ, the Nevada Test Site and Fallon Naval Air Station, who assisted in the experiments.

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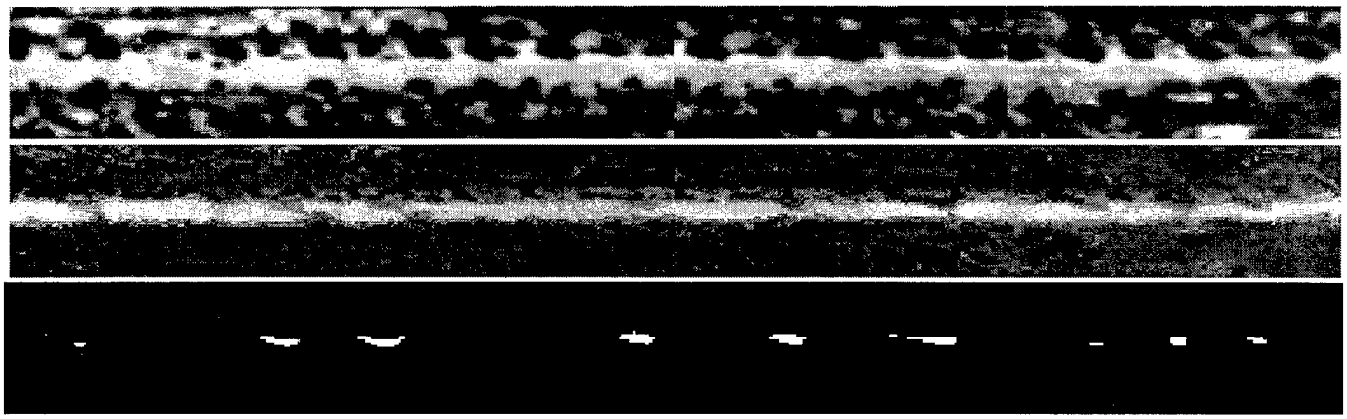


Figure 3. Detection of Road Mines in Hyperspectral image Data. Broad band LWIR image of road (top) does not show the mines. The spectral false color image (center) shows the mines but with off-road false alarms. The thresholded output of a quadratic detector algorithm (on bottom) shows only the detected mines, with no false alarms.

On the feasibility of microwave imaging of buried land mines at modest stand-off distance

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Abstract – This paper describes feasibility tests of a concept for a vehicle carried, microwave system for imaging land mines at distances 5 to 10 meters ahead of a vehicle. The system would have antenna arrays and multiple discrete frequencies to acquire data. The paper presents images from data measured with a transmitting antenna and a translated receiving antenna.

I. INTRODUCTION

Land mine detection is a difficult technical problem because it involves many variables including mine configuration, size, composition, and depth as well as diverse soil properties. Many sensors have been developed for detection. These include electromagnetic induction detectors, ground penetrating radars, and infrared cameras. These sensors are useful but have deficiencies. For example, induction methods detect metallic but not dielectric mines. Radars can detect both metallic and dielectric mines but to our knowledge do not detect small, non-metallic mines. For infrared systems, mine depth and sunlight variation can limit detection. These problems have stimulated the development of multi-sensor systems and data fusion, but work continues on improving sensors.

In addition to the influence of sensors, the effectiveness of a mine detector depends on its configuration. The most common detectors seem to be those that are hand held, with a sensor on a boom, about a meter ahead of the operator. Hand held systems are slow and hazardous. Therefore, airborne and vehicular systems are being developed to distance the operator from mines and to accelerate searches.

This paper describes feasibility tests of a concept for a vehicular, microwave system that would image mines at distances 5 to 10 meters ahead of a vehicle. The purpose of the tests was to examine physical, scattering mechanisms underlying imaging and to test the imaging algorithm, which has been utilized for short range and vertical incidence, at oblique incidence [1]. The motivation for imaging is identification, which can accelerate searches.

Section II describes the system concept, and Section III summarizes the image formation theory. Sections IV and V describe initial measurements and image calculations that were done to test feasibility. The measurements did not use an antenna array; instead, an antenna scanned a linear path, and another, fixed antenna transmitted. Mine targets were at distances approximately 3-1/2 meters from the antennas

Section IV describes results for a 12-inch diameter, non-metallic mine on a paved surface. It presents an image which is a range profile generated from reflections for 26 frequencies in the band 5 to 6 GHz. This image suggests wave mechanisms, reflections from the mine's front and back surfaces.

Section V describes results for the 12-inch mine buried in damp soil. It shows a plan view image computed from data for frequency 2 GHz. Section V also presents a range profile generated from 101 frequencies in the band 2 to 6 GHz. These images also suggest reflection mechanisms. For comparison, an image was formed of a metal plate, from specular returns.

II. SYSTEM CONFIGURATION

Figs. 1 and 2 suggest the configuration of a vehicular system. An antenna radiates continuous waves at a sequence of discrete frequencies, and an array of receiving antennas spatially samples the reflected fields. The receiver measures phase and amplitude. A computer processes the digitized reflected field data into images by an algorithm based on angular spectrum diffraction theory.

The system in Fig. 1 can be generalized to include a vertical array of transmitting antennas. An early prototype for imaging objects in air was described in [2].

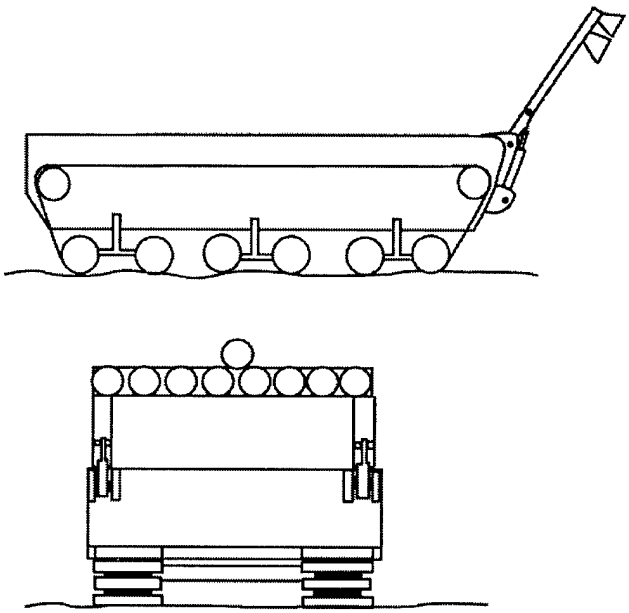


Fig. 1. Antennas on vehicle. The line array receives. The upper antenna transmits.

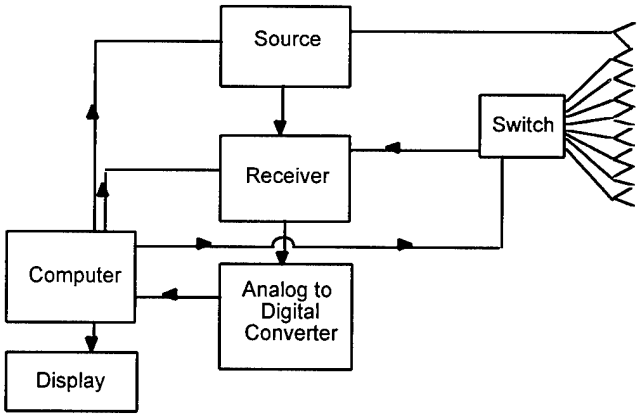


Fig. 2. System block diagram

III. THEORY

The complex-valued reflectance data are processed into images in two ways. The first way utilizes data from one receiving antenna. The reflectance values for a set of frequencies are Fourier transformed to synthesize a pulse that gives object range

$$u(t) = \sum_{k=0}^{N-1} u_k \, e^{i2\pi(2r/c)f_k} \qquad (1)$$

where u_k is reflectance at frequency f_k, r is slant range, and c is the speed of light in air. Note that propagation in soil is omitted so that Equation 1 applies to mines on the surface or at depths small relative to wavelength.

The second processing method utilizes data over antenna positions for each frequency. The first step is to form the angular spectrum.

$$u(\mu) = \sum_{k=0}^{N-1} u_n \, e^{-i2\pi\mu x_n} \qquad (2)$$

where u_n is the received field at antenna co-ordinate x_n, and μ is spatial frequency. The spectrum is evaluated at distance d by the propagator function, which, for wavelength λ, is

$$P(\mu) = \exp\left[-i2\pi\left(\lambda^{-2} - \mu^{-2}\right)\right]^{1/2} d \qquad (3)$$

The image u_I, as a function of image co-ordinate x_i is given by inverse transformation

$$u_I(x_i) = \sum_m u(\mu_m) P(\mu_m) e^{i2\pi\mu_m x_i} \qquad (4)$$

Sampling is a significant consideration. The frequency sampling interval must be small enough to avoid ambiguities. Commercial, laboratory sources and receivers are adequate, and we have developed more compact, special purpose equipment. Spatial sampling interval must be small enough to avoid multiple images. Spatial sampling is set by the diameter of individual antennas in an array. For example, for frequency 2 GHz, spatial sampling interval can be up to 5.08 cm. To avoid ambiguities and achieve antenna gain, two staggered rows of receiving antennas can be used to extend the frequency band.

IV. RESULTS FOR A SURFACE MINE

This section describes measurements and an image for a 12-inch diameter, non-metallic mine simulant that was on a paved surface. Fig. 3 shows the experimental setup. The mine's center was at ground range 132 inches. A stationary, vertically polarized hour antenna, aperture 4 x 8 inches transmitted, and a single, vertically polarized receiving antenna, aperture 2-1/2 x 4 inches, scanned a 60-inch long path. The antennas were 56 inches above the paved surface. Frequencies were from 2 to 6 GHz in 0.04 GHz steps. A

network analyzer was the transmitter and receiver, and a personal computer controlled the analyzer and digitized data.

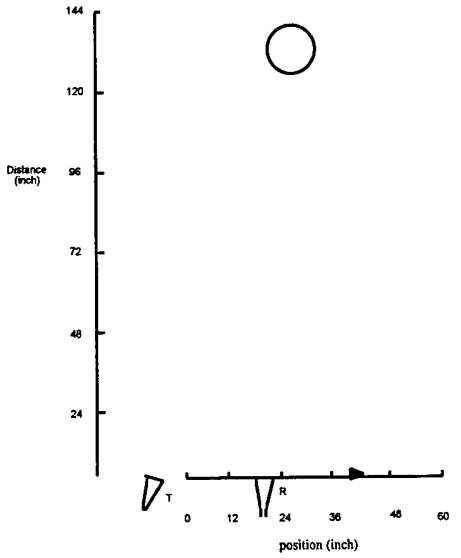


Fig. 3. Bistatic arrangement for measurements with a mine stimulant on a paved surface. The receiving antenna is labeled R; the transmitting, T. Vertical polarization. Antenna heights were 52 inches. (BPL*2)*

Fig. 4 shows a range profile calculated by evaluating Equation 1 for frequencies from 5 GHz to 6 GHz in 0.04 GHz steps. The image in Fig. 4 suggests reflections from the mine's front and back surfaces.

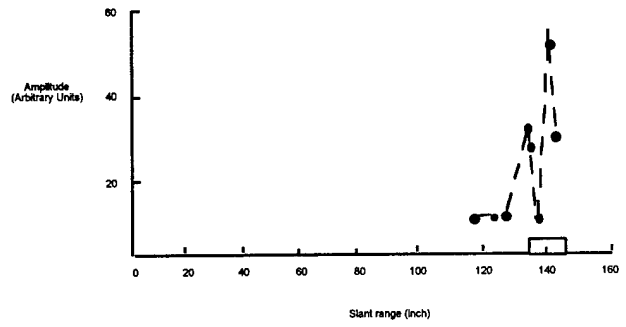


Fig. 4. Calculated image by forming a pulse from measurements between 5 and 6 GHz for the arrangement in Figure 3.

V. Results for a Buried Mine

This section describes measurements and an image of the 12-inch diameter non-metallic mine simulant buried in damp soil. The top of the mine was 1-1/2 inches below the soil surface. Fig. 5 shows the setup. A fixed vertically polarized horn antenna, aperture 4 x 8 inches transmitted, and a horn antenna, aperture 2-1/2 x 4 inches, scanned a 60-inch long path. The center of the mine was 136 inches from the antenna scanning line. Antennas were 54 inches above the soil surface. Reflectance was measured for distinct frequencies between 2 and 6 GHz, at intervals of 0.04 GHz during antenna motion.

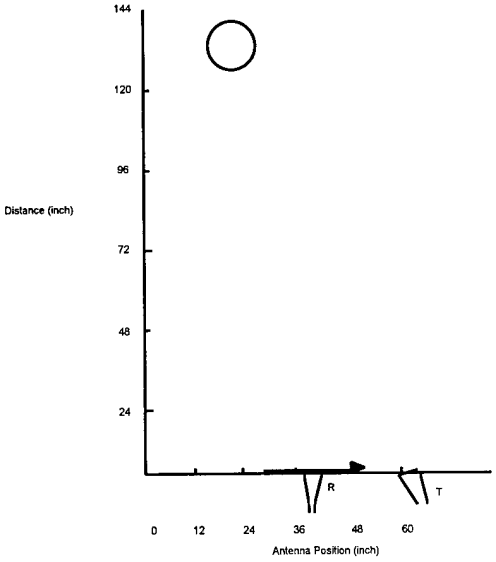


Fig. 5. Arrangement for measurements on buried mine simulant. The transmitting antenna T was fixed in position. The receiving antenna R was translated. Antenna heights were 52 inches above the ground surface. Polarization was vertical. (229GG)

Figure 6 shows a plan view generated by evaluating Equation 4 with data from the interval 24 to 48 inches in Fig. 5. Frequency was 2 GHz. Image values were calculated for three values of slant range, 132, 136, and 140 inches. In this image, the shaded regions show where amplitude exceeded 0.7 times the peak amplitude, which occurred for ranges 132 and 140 inches.

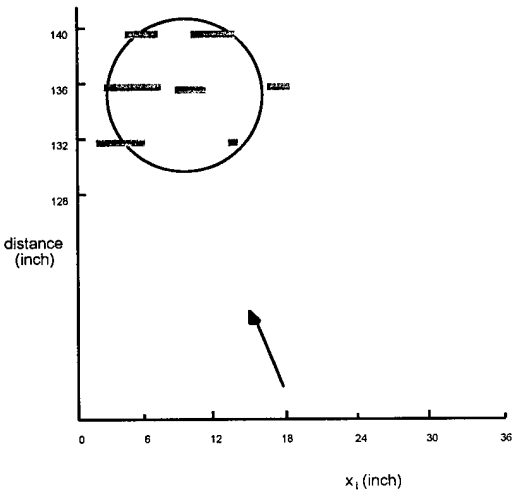


Fig. 6. Image for 12-inch mine simulant buried 1-1/2 inches in damp sand. Frequency: 2 GHz; polarization: vertical. The arrow shows the direction of the incident wave normal.

Although the calculations are sparse, they do suggest the object's shape. The image also suggests that reflections occur at the object's boundaries as well as at the center.

Range profiles were calculated using frequencies from 2 to 6 GHz in .04 GHz steps. As a preliminary, to test accuracy, an image was formed of a 6-inch square metal plate arranged for specular return to the 24-inch position of Fig. 5; the mine was absent. The image, shown in Fig. 7, was computed for data from the 24-inch position. A range profile of the buried (1-1/2 inch deep) mine was computed from data for frequencies 2 to 6 GHz in .04 GHz steps. Again, the data were for the 24-inch position in Fig. 5. The profile is in Fig. 8.

The range profile for the plate shows a sharp peak at the plate's position. The range profile for the mine suggests multiple reflections.

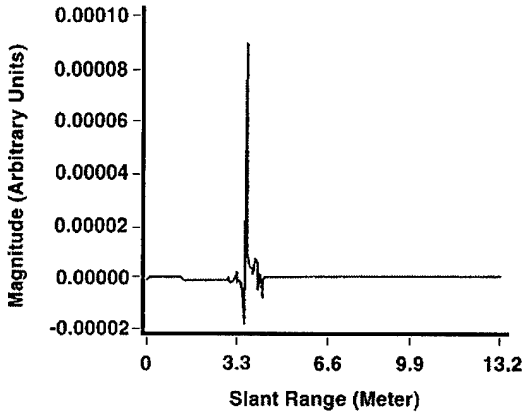


Fig. 7. Range profile of 6-inch square plate

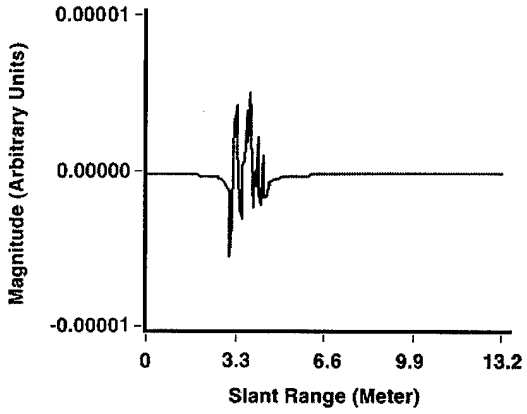


Fig. 8. Range profile for buried mine

VI. SUMMARY

The paper presented an approach to imaging land mines at distances of 5 to 10 meters ahead of a vehicle. The approach uses a band of discrete microwave frequencies, a transmitting antenna, and an array of receiving antennas. The system synthesizes a line array of reflectance data, which are digitally processed to form images which are range profiles or plan views.

The paper described measurements for a 12-inch diameter, non-metallic mine simulant. The measurements were made with a fixed transmitting antenna and with a receiving antenna scanned on a linear path. Images were formed for the mine on a paved surface and buried 1-1/2 inches in damp soil, at distances approximately 3.4 meters. The images suggest multiple wave reflection mechanisms.

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CHEMICAL SYSTEMS FOR IN-SITU NEUTRALIZATION OF LANDMINES IN PEACETIME

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ABSTRACT

The world is polluted with an estimated 110 million mines in 62 countries. Worldwide, more than 10,000 civilians are killed or wounded by landmines every year. The detection, mapping, and marking of these mines are essential precursors for their clearance and neutralization. Subsequently, reliable and safe means for in-situ mine neutralization are essential. Two prototype delivery systems for the in-situ chemical neutralization of landmines in operations other than war (OOTW) were developed and demonstrated as part of the FY-1995 Congressionally directed Humanitarian Demining Technology Program. Both are simple, low-cost, and safe for neutralizing exposed and buried explosive ordnance. These two delivery systems, as well as field-test results of their demonstrated performance against unfuzed and fuzed live anti-personnel and anti-tank mines, are presented and discussed. Safety, user interface, target mine types, effectiveness, and potential applicability in humanitarian demining environments are discussed.

INTRODUCTION

Landmines are considered essential weapons of war; but their deadly and devastating effects on innocent civilian populations remain long after warfare has ended. The indiscriminate proliferation of mines in wartime leads to the killing and maiming of an estimated 10,000 people, mostly civilians, every year [1]. Many of the 110 million mines polluting over 60 countries in the world are capable of killing or disabling several people. Efforts to clear these mines are slow, hazardous, and expensive. A cheap anti-personnel (AP) landmine that costs a few dollars may require up to one thousand dollars to be cleared. Anti-tank (AT) landmines are not necessarily hazardous to individuals, but they are capable of destroying machinery and vehicles that encounter them. The detection and removal of landmines thus becomes almost impossible for many poor and developing nations. Landmine warfare has advanced to the point that in some nations whole populations are hostage to the fear of death and dismemberment by these hidden killers. The landmine problem must be recognized for what it is: a crisis of global proportions.

In an effort to mitigate this global landmine crisis, the U.S. Congress in 1995 directed the Department of Defense to initiate a research and development program to optimize the speed and safety of demining with the mission to develop new equipment and techniques for detecting, marking, and clearing landmines, using off-the-shelf materials and technologies.

At present there are only two demining techniques to clear individual AP and AT landmines: (1) manually removing the mines and (2) demolition of the mines using high explosives. Clearing mines manually is a difficult, slow, tedious, and very hazardous operation. Demolition with high explosives such as composition C4 is also very hazardous and costly, but more importantly requires specialized training in explosives handling and use. In both cases, direct access to the mines is required; buried mines in general have to be uncovered. Furthermore, detonating metallic mines creates more fragments in and upon the soil which create greater difficulty in detecting actual mines with metal detectors. This complicates quality assurance for declaring areas safe for returning refugees. In addition, the demolition explosives such as Composition C4 may be stolen or otherwise appropriated by terrorists.

Therefore, the U.S. Congress tasked the U.S. Army and its countermine scientists and engineers from the Communications and Electronic Command's (CECOM) Night Vision and Electronic Sensors Directorate (NVESD) to investigate the humanitarian demining equipment and technology requirements by leveraging new, unique, proven and/or promising technologies that are capable of being successfully used for demining operations. The Environmental Systems Branch of the Countermine Division of the U.S. Army successfully executed this program. In particular, as described here, the in-situ chemical neutralization of landmines has been designed, demonstrated, and evaluated by IIT Research Institute, in support of CECOM-

NVESD, to improve the world's capability in humanitarian demining operations.

BACKGROUND

The main explosive charge in almost all foreign and domestic landmines is typically TNT and TNT-based explosives such as Composition B (Comp. B), amatol, picratol, etc. [2]. Explosives contain considerable oxygen within their metastable molecules; hence, they do not need air in order to detonate, deflagrate, or dissociate by autocatalytic decomposition. Most explosives can dissociate by alternative mechanisms, and dissociation by detonation generally involves an entirely different mechanism than by autocatalytic dissociation/decomposition. TNT will generally burn fiercely but without transition to detonation if simply ignited; i.e., without use of a detonator and explosive booster charge to shock-initiate the TNT. Hence, if a stimulus means such as a chemical hypergol or radiant-energy laser is capable of "directing" the dissociation mechanism into autocatalytic decomposition in lieu of detonation, it is likely that detonation will be precluded. The chemical transformation of TNT, as well as most other organic secondary explosives, can proceed by four general mechanisms as follows:

1. Burning; simple combustion in air (oxygen),
2. Heterogeneous (stoichiometric) chemical reaction,
3. Detonation, and
4. Autocatalytic decomposition.

Open-pit burning had been a common practice for the disposal of propellents and explosives; the materials were placed in open trenches, covered with straw and drenched in kerosene or fuel oil, then ignited. Exposed to adequate air, combustion proceeded to completion. Because of its dependence upon oxygen, burning of confined, often buried ordnance is not feasible. Heterogeneous chemical reaction of explosives with suitable chemical reagents is effective [3,4] but requires excessive (stoichiometric quantities of such reagents, and there is no practical, effective delivery system for in-situ neutralization, especially in the case of buried mines. Detonation of explosive ordnance is a viable option that is in practice, but as discussed earlier has considerable drawbacks. Autocatalytic decomposition is the simplest, cheapest, and most effective option for chemical neutralization of landmine explosives. This type of chemical neutralization is most readily achieved by using suitable chemicals that are hypergolic with the explosives; e.g., metal alkyls and aliphatic amines. Very small amounts, even several drops in laboratory tests, cause nearly instantaneous hypergolic ignition of TNT, Comp. B, and most other explosives used in landmines, leading to the non-detonative autocatalytic decomposition/self-consumption of the entire explosive charge [5,6]. Ignition is achieved at even sub-zero temperatures with some hypergols; e.g., diethylzinc (DEZ) reacts hypergolically with TNT powder even at -30^{0}C within a matter of seconds.

CURRENT INVESTIGATION

Two prototype remotely-operated chemical delivery systems have been developed for the in-situ chemical neutralization of the main explosive charge in landmines [7,8]. The first, System No 1, referred to as "bullet with chemical capsule" (BCC), uses a small quantity of an amine or metal alkyl in a plastic capsule that is placed just above the landmine using a simple tripod. A bullet, shot through the capsule and into the mine, ruptures the capsule, penetrates the overburden and the mine casing, and enters into the explosive charge, carrying the dispersed chemical hypergolic reagent into the explosive charge inside the mine. Within seconds a highly exothermic, hypergolic autocatalytic self-destruction of the explosive charge takes place. Within minutes, depending on the size of the explosive charge, the mine is chemically neutralized. The second, System No. 2, referred to as "chemical-filled projectile" (CFP), shoots a cartridge-case projectile into the mine in such manner that the projectile penetrates the mine casing and enters the explosive, rupturing the cartridge case to release a metal alkyl into the penetrated explosive. This similarly causes a hypergolic, highly exothermic autocatalytic complete destruction of the explosive. Both systems are effective against TNT and Comp. B, the major explosives in landmines, as well as other explosives such as tetryl. The major advantage of this chemical neutralization methodology is that complete, non-detonative neutralization of the explosive component in the mines is achieved, without detonation damage to the area or contamination by mine-casing debris, especially in the case of metal-encased landmines.

Major effort was placed into design and development of these prototype remote-operated delivery systems, which are sufficiently robust to be reusable. For expediency, an over-kill scenario was adopted for delivery System No. 1 in that hypergol reagent loss due to dispersal by the bullet and absorption into the overburden would limit the amount actually entering the mine and reacting with the explosive. The amine diethylenetriamine (DETA) was selected for this system. It was demonstrated that 60 mL of DETA should suffice for mines buried under 305 mm of overburden. For the second delivery system, hypergol reagent loss was not of concern since the cartridge delivered the reagent directly into the explosive within the mine casing. Hence, in the case of this system nominally 5 mL DEZ was effective.

DELIVERY SYSTEMS

Both delivery systems are operated remotely using an electric squib, and a tripod for positioning the delivery devices above the mine. In the case of system No. 1 (BCC), illustrated in Fig. 1, the chemical-filled plastic capsule bottle is secured inside a quick-disconnect reducer assembly at the bottom of the "gun" tube.

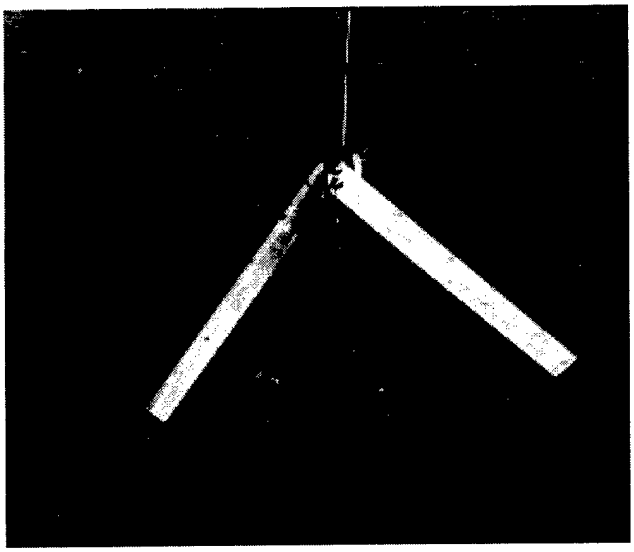


Figure 1

After the squib is fired, it produces gas pressure which drives a hammer which impacts a firing pin. This in turn fires a cartridge, and the bullet penetrates the chemical filed capsule, overburden (if any), the mine casing, and the main explosive charge, thereby shattering a portion of the explosive charge. The amine follows-through behind the bullet and contacts the explosive charge, causing hypergolic ignition and autocatalytic decomposition of the explosive charge. Except for the amine capsule, the cartridge, and the squib, the delivery system is reusable for the next mine.

In the case of System No. 2 (CFP), the function is similar, except that a spent 7-mm or 0.50 caliber cartridge case serves as the hypergol liquid-filled vehicle. The bullet is replaced by a tapered penetrator, which upon impact with the mine casing is forced further into the cartridge case. This causes the latter to rupture as designed by its scoring, which allows the hypergolic liquid to be injected into the explosive charge of the mine. This then also causes hypergolic ignition and autocatalytic decomposition of the explosive charge inside the mine. This system has potential to neutralize not only buried mines, but mines under water and surface-emplaced mines/ordnance from a distance. The requisite propellent was reloaded into blank .38-caliber cartridge cases to the extent required to achieve penetration of the overburden (if any) and the mine casing.

FORT A. P. HILL DEMONSTRATION TESTS

Both of the above-described chemical delivery systems were tested at Fort A.P. Hill in November 1995 against surface-buried fuzed and unfuzed anti-personnel (AP) and antitank (AT) landmines having metal, wood, and plastic casings. Tests were conducted with both delivery systems against: (a) wooden-case PMD-6 AP unfuzed mines with 0.2 kg TNT; (b) metal-case simulated M-16 unfuzed mines with 0.521 kg cast TNT; (c) plastic-case PMN-2 fuzed AP mines with 0.108 kg Comp. B; and (d) AT mines: one unfuzed plastic-case M-19 (9.53 kg Comp. B), one unfuzed wooden-case TMD-44 (7.0 kg TNT), one unfuzed metal-case M-15 (10.33 kg Comp. B), and one fuzed metal-case M-15 (10.33 kg Comp. B).

The results of these tests are presented in Tables 1 and 2. Table 1 presents results with System No. 1 (BCC) and Table 2 presents results with System No. 2 (CFP). The ambient temperature was approximately 10^0C during the tests. Although neither delivery system is considered expendable at this stage of development, they both function in a standoff manner and are sufficiently robust that, even in the unlikely event of detonation of an AP mine, the delivery hardware would not be seriously damaged. In tests against actual fuzed AP and AT mines, both of these delivery system initiated the non-detonative autocatalytic self-consumption irrespective of the fuzing. Nevertheless, effort is underway to simplify these delivery systems further and to fabricate them from expendable materials. Note that in the case of the CFP system, the delivery system would emulate shooting at the landmines with a rifle.

TABLE 1. FORT A.P. HILL TEST RESULTS OF CHEMICAL NEUTRALIZATION SYSTEM NO. 1, BULLET WITH CHEMICAL CAPSULE (BCC), AGAINST VARIOUS AP AND AT LANDMINES. CHEMICAL HYPERGOL, 60 ML. DIETHYLENETRIAMINE (DETA).

Test Nos.	Mine type	Casing	Explosive	Fuzed	Chemical Neutralization
1,2,3	AP PMD-6	wood	TNT	no	complete
4,5,6	AP* M-16	steel	TNT	no	complete
7,8,9	AP PMN-2	plastic	Comp B	yes**	complete
10	AT M-19	plastic	Comp B	no	complete
11	AT TMD-44	wood	TNT	no	complete
12	AT M-15	steel	Comp B	no	complete
13	AT M-15	steel	Comp B	yes	complete

* Simulated mine.
** Fuzed with detonator

As indicated in Table 1, all tests were conducted with 60 mL of DETA regardless of the type of mine or mine casing. Since in well-controlled laboratory experiments only a few drops of DETA are adequate to hypergolically initiate the autocatalytic decomposition of TNT and Comp. B, the 60 mL was believed to be a considerable excess. However, for the purposes of these qualitative tests, this was a calculated condition to overcome unknown influences of parameters such as temperature, type and form of the explosive, confinement, presence of foreign materials, and the actual dynamics of the delivery process. In tests with Comp. B the explosive charge was completely consumed. In tests with TNT the explosive was also completely consumed, except that a small amount of carbonaceous residue remained. In all tests the initial hypergolic response occurred within a few seconds and intense smoke and flame appeared throughout the neutralization process which persisted for about 5 to 45 minutes depending on the amount of explosive and other factors. In tests with fuzed mines neutralization occurred without initiation of detonation. It is interesting that for the AT wooden mine, which had 7.0 kg of TNT wrapped in heavy wax paper, all the TNT was completely neutralized without the mine casing being burned; i.e., no flames were observed throughout the neutralization process.

TABLE 2. FORT A.P. HILL TEST RESULTS OF CHEMICAL NEUTRALIZATION SYSTEM NO. 2, CHEMICAL FILLED PROJECTILE (CFP), AGAINST VARIOUS AP AND AT LANDMINES: CHEMICAL HYPERGOL, 5-15 ML. DIETHYLZINC (DEZ).

Test Nos.	Mine type	Casing	Explosive	Fuzed	Chemical Neutralization
1*** 2***	AP PMD-6	wood	TNT	no	partial
3***	AP PMD-6	wood	TNT	no	YES-complete
4*** 6***	AP* M-16	steel	TNT	no	partial
5***	AP* M-16	steel	TNT	no	YES-complete
7,8,9	AP PMN-2	plastic	Comp B	yes**	partial
10	AT M-19	plastic	Comp B	no	YES-complete
11***	AT TMD-44	wood	TNT	no	partial
12	AT M-15	steel	Comp B	no	NO-malfunction
13	AT M-15	steel	Comp B	yes	NO-malfunction

* Simulated mine.
** Fuzed with detonator
*** In these tests the DEZ was diluted with 20 percent toluene.
Note: Test Nos. 1,2,3,7,8 and 9 had 4.5 mL hypergol; the remainder had 15 mL.

As indicated in Table 2, in some tests the DEZ hypergol was diluted with 20 percent toluene to mitigate its pyrophoricity. Because of this pyrophoricity (spontaneous ignition in air), unless the projectile penetrated the mine casing and discharged the DEZ directly into the explosive, it was consumed by nearly instantaneous combustion in air. In the case of Test Nos. 12 and 13, inadequate propellant charge prevented the projectile from penetrating the heavy steel casing of these AT mines; hence, the hypergol did not come in contact with the explosive.

This delivery system is very design intensive, but is believed to have much greater applicability once design aspects are resolved. Its potential advantages include the following: (1) It requires a much smaller amount of hypergol because it delivers it directly into the explosive; (2) It is capable of penetrating soil to neutralize buried mines (the BCC System has already been demonstrated to neutralize buried mines up to 305 mm); (3) It should be effective against mines under water; and (4) It should be capable of neutralizing exposed landmines from a distance.

APPLICABILITY FOR HUMANITARIAN DEMINING

The chemical neutralization systems described here are in the prototype stage and are under further design and development to meet the requirements of the U.S. Congress that they be shared in an international environment. These in-situ chemical neutralization systems meet the requirements of humanitarian demining such as low cost, simple ease of operation, safe, effective, environmentally safe, and capable of being shared in an international environment. These are described separately as follows:

LOW COST: The United Nations estimates that the aggregate cost for mine clearance is from US $200 to US $1000 per mine. However, many third-world countries' annual GDP is only US $200. It is estimated that these chemical neutralization systems, when adequately developed, would cost less than US $10 per mine. The systems are reusable; the expendable items are simply a small amount of chemical, a plastic capsule, bullet/cartridge, and squib or time delay fuze. The systems do not require the use of explosives.

SIMPLE EASE OF OPERATION: This is one of the most important requirements of humanitarian demining because in-situ neutralization of mines will be operated by indigenous people. These chemical delivery systems are simple and need only chemical-filled capsules or projectiles, bullet/cartridges, and squibs or time delay fuzes. Both systems are operated remotely and do not require any rigorous training.

EFFECTIVENESS: Both delivery systems are effective against mines containing TNT and Comp. B. Experiments have also been conducted that demonstrated the BCC systems containing

DETA to be effective against tetryl. It is also believed that (1) TNT-containing explosives such as amatol, pentolite, and picratol would be neutralized by using either system, and (2) the same could be said for explosives containing a nitroaromatic ring such as picric acid. The BCC system No. 1 is simpler and is currently well advanced. The CFP System No. 2 is at a lesser advanced stage, but has greater versatility. Both systems need further investigation to be applicable against all types of mines and explosives, and under all realistic conditions.

SAFETY: Neither of the delivery systems uses explosives, and the hypergolic chemicals are not especially hazardous; they are used routinely in industrial processes. However, because of its pyrophoric characteristic, DEZ must be handled in an inert, dry environment. This problem can be, and has been, mitigated by dilution of the DEZ with up to 50 percent hydrocarbon such as toluene, without unduly reducing its hypergolicity with explosives. Furthermore, the hazard exists only in loading the capsules or cartridges, which can be done in production quantities, since storage is not a problem nor a great hazard.

SHARING IN THE INTERNATIONAL ENVIRONMENT: The in-situ chemical neutralization of landmines does not use explosives which might be compromised into terrorist activities. Because these systems do not use explosives, they are not subject to the extensive rules and regulations of handling / transport / storage / use of explosives.

SAFE TO THE ENVIRONMENT: Chemical neutralization of landmines involves the non-detonative autocatalytic decomposition of the main explosive charges such as TNT and Comp. B. The products are gases such as carbon monoxide and dioxide, nitrogen, water vapor, and carbon particles as major products. Hence toxic contamination of air, soil, and water is not a problem. Because the processes do not involve detonation of the explosives, they do not produce metallic fragments in or on the soil, except for the burned-out empty metal casings; wooden and plastic casings are simply melted or, at worst, burned. This is an important factor for quality assurance.

DISCUSSION: Both of these chemical neutralization systems will neutralize surface buried or buried mines to acceptable depths; however, the chemical-filled projectile system should neutralize mines under water, and its application to neutralization of surface mines remotely from a tank or helicopter is feasible. These chemical systems can be applicable for clearing unexploded ordnance (UXO), both exposed and buried. The chemical neutralization of mines without detonations is highly desirable, but application to humanitarian demining needs further investigation, especially to develop an appropriate single chemical reagent composition to be effective against all types of main charge explosives in landmines.

CONCLUSIONS

Chemical neutralization technology is based on the use of hypergolic chemical reagents that initiate the autocatalytic decomposition/self consumption of the main explosive charges in landmines. Two categories of chemical hypergols were demonstrated to be effective. The amine hypergol DETA was deemed more effective for the BCC System No. 1 whereas the metal alkyl DEZ was better suited for the CFP System No. 2. However, both hypergols are effective in both systems; furthermore, a combination of these hypergols could prove to be even more effective by combining the better hypergolic properties of both.

These chemical neutralization systems were effective against both TNT and Comp. B landmine explosive charges. Their effectiveness against most other explosives found in landmines must be determined. The principle advantage of chemical neutralization is that it leads to complete, non-detonative destruction of landmines. The requisite hypergolic reagents are readily available commercially and are relatively cheap; especially when only a few milliliters are needed per mine. However, the major advantage of these chemical neutralization systems is that they do not require explosives, so that the associated critical handling, storage, transportation, and safety restrictions are not required.

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Radar Imaging Experiments for Landmine Detection

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In previous reports, we have described a miniature radar called Micropower Impulse Radar (MIR) developed at the Lawrence Livermore National Laboratory (LLNL) for many applications in short-range motion sensing, ranging and underground imaging. This new radar technology is compact, low-cost, low power, and can easily be assembled into arrays to form complete ground penetrating radar imaging systems. We have coupled a single transmit/receive sensor with imaging software running on a portable laptop computer to generate synthetic aperture images of anti-tank mines. LLNL has also developed tomographic reconstruction and signal processing software capable of producing high-resolution 2-D and 3-D images of objects buried in materials like soil or concrete from stand-off radar data. Preliminary test results have shown that a radar imaging system using these technologies has the ability to image both metalic and plastic anti-vehicular mines in up to 15 cm of moist soil. We have since made extensions to the MIR and tested it under various conditions. In particular, we have shown detections of anti-personnel mines in cluttered environments and have designed an array of MIRs that could be man-portable. The MIR already solves many issues inherent with most ground-penetrating radar systems; i.e., the size, weight, power-use, and cost are all extremely favorable for AP mine detection. In this presentation, we wil present work in progress to show the efficacy of the MIR to the mine detection problem.

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Ultra-Wideband, Short Pulse Ground-Penetrating Radar: Theory and Measurement

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Ultra-wideband (UWB), short-pulse (SP) radar is investigated theoretically and experimentally for the detection and identification of three-dimensional anti-tank and anti-personnel mines buried in and placed atop soil, as well as buried under and embedded in snow. The calculations are performed using a rigorous, three-dimensional Methods of Moments algorithm for metal mines and the Born approximation for dielectric (plastic) mines. With regard to the electrical properties of the soil and snow, we use measured parameters from 100 MHz to 1.5 Ghz. In the calculations, we compute the UWB, SP scattered fields as well as the target late-time resonant frequencies. The measurements are performed using a novel UWB, SP synthetic aperture radar (SAR) implemented on a mobile boom. Experimental and theoretical results are compared.

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