



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

**CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS
EDUCATION AND RESEARCH (CRUSER) FY14 ANNUAL
REPORT: CONCEPT EXPLORATION**

Prepared by

Lyla Englehorn, Faculty Associate – Research

September 2014

Approved for public release: distribution unlimited

Prepared for: Raymond R. Buettner Jr., CRUSER Director

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 30 September 2014		2. REPORT TYPE Technical Report		3. DATES COVERED (From-To) 1 Oct 2013 – 30 Sept 2014	
4. TITLE AND SUBTITLE Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) FY14 Annual Report: Concept Exploration			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Lyla Englehorn, MPP			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Postgraduate School (NPS) 1 University Circle Monterey CA 93943			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Deputy Undersecretary of the Navy – PPOI 100 Navy Pentagon Room 5E171 Washington, DC 20350 Office of Naval Research (ONR) One Liberty Center, 875 North Randolph Street, Suite 1425 Arlington, VA 22203-1995			10. SPONSOR/MONITOR'S ACRONYM(S) DUSN/ONR		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution unlimited					
13. SUPPLEMENTARY NOTES This report is not the work of one author, but a compilation of event reports and funded research summaries for FY14					
14. ABSTRACT The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems (UxS) education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems (UxS) in military and naval operations. This FY14 annual report summarizes CRUSER activities in its fourth year of operations (2014), and highlights future plans.					
15. SUBJECT TERMS robotics, unmanned systems, UxS, UAV, USV, UGV, UUV					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 166	19a. NAME OF RESPONSIBLE PERSON Lyla Englehorn
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			
					19b. TELEPHONE NUMBER (include area code) 831-656-2615

THIS PAGE INTENTIONALLY LEFT BLANK

**NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000**

Ronald A. Route

President

Douglas A. Hensler

Provost

The report entitled “*Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) FY14 Annual Report: concept exploration*” was prepared for the Office of Naval Research (ONR), One Liberty Center, 875 North Randolph Street, Suite 1425, Arlington VA 22203-1995

Further distribution of all or part of this report is authorized.

This report was prepared by:

Lyla Englehorn, MPP
Faculty Associate – Research

Reviewed by:

Raymond R. Buettner Jr., PhD
CRUSER Director

Released by:

Jeffrey D. Paduan, PhD
Dean of Research

THIS PAGE INTENTIONALLY LEFT BLANK

Unclassified; distribution is unlimited

**CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS
EDUCATION AND RESEARCH (CRUSER):**

FY14 Annual Report

Concept Exploration



Prepared by Lyla Englehorn, CRUSER Director of Concept Generation
for Dr. Raymond R. Buettner Jr., CRUSER Director
and Dr. Timothy H. Chung, CRUSER Deputy Director

NAVAL POSTGRADUATE SCHOOL

September 2014

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

EXECUTIVE SUMMARY	VI
I. BACKGROUND	1
A. VISION	2
B. MANAGEMENT	3
C. FY14 PROGRAM ACTIVITY SUMMARY	4
II. PRIORITIES	5
A. EDUCATION	7
1. Education Projects	7
<i>a. An Integrated Indoor Unmanned System Experimentation Facility for Campus-wide Teaching and Research</i>	<i>8</i>
<i>b. A Student built Autonomous Ground Vehicle as a Course Project for the Benefit of the CRUSER Community</i>	<i>11</i>
<i>c. Introduction to Big Data and Analytics Course Development</i>	<i>15</i>
<i>d. A Manual for the Model-Based Design and Assessment of Robotics and Unmanned Systems</i>	<i>17</i>
2. Education Initiatives	18
<i>a. Continuing Education: Robo-Ethics, March 2014</i>	<i>18</i>
<i>b. CRUSER Scholars and STEM Outreach</i>	<i>21</i>
3. NPS Course Offerings and Class Projects	22
<i>a. Systems Engineering Analysis (SEA) 20, 2014</i>	<i>22</i>
<i>b. Search Theory and Detection (OA3602), Spring 2014</i>	<i>23</i>
<i>c. Joint Campaign Analysis (OA4602), Winter and Summer 2014</i>	<i>23</i>
<i>d. Advanced Applied Physics Lab (PC4015), Winter and Summer 2014</i>	<i>23</i>
<i>e. Policies and Problems in C4I (CC4913), Spring 2014</i>	<i>24</i>
4. NPS Student Theses	24
5. Student and Faculty Travel	28
B. RESEARCH AND EXPERIMENTATION	29
1. Diver and Unmanned Vehicle Networking-by-Touch	30
2. UUV Path Planning for ASW/MIW Using Navy's Ocean Data	37
3. Innovating for the Swarm vs. Swarm Grand Challenge Competition	42
4. A Robot Control Ontology Supporting Ethical Mission Execution	45
5. Joint Human/Robot Operations in Extreme Environments	47
6. Robotic Outposts to Support Persistent AUV Operations	50
7. AUV Operations in Extreme, Under-Ice Environments	54
8. Development of Very-Small Multi Rotor Aircraft as Platforms for Atmospheric and Sea Surface Measurement	57
9. A Tele-Operative Sensory-Motor Control Platform (TSMCP)	62

10.	Tropical Cyclone Reconnaissance with the Global Hawk: Assessment of Initial Results and Use in Improving Forecasts of Tropical Cyclone Intensity and Structure.....	63
11.	Short Range Radiative Wireless Power Transfer (WPT) for UAV/UAS Battery Charging.....	63
12.	Aqua-Quad	70
13.	Glider applications in Tactical Oceanography	76
14.	Defense against Swarms: A Key Naval Capability	79
15.	NPS-NAVAIR UAS IFC Challenge.....	80
16.	Command & Control of Highly Autonomous Systems and People.....	84
17.	Real-time undersea networking using acoustic communications for improved AUV positioning and collaboration	90
18.	Environmental Data Collection Using Autonomous Wave Gliders.....	93
C.	CONCEPT GENERATION.....	97
1.	Warfare Innovation Workshops.....	97
2.	CRUSER Technology Continuum (TechCon), April 2014	100
D.	OUTREACH AND RELATIONSHIPS.....	102
1.	Community of Interest	103
2.	4th Annual Robots in the Roses Research Fair, April 2014.....	105
3.	ONR-Reserve Component Relationship	106
4.	Briefings	106
III.	CONCLUSION	108
A.	PROPOSED FY15 ACTIVITIES.....	108
B.	LONG TERM PLANS.....	109
APPENDIX A: PRESENTATIONS, PUBLICATIONS AND TECHNICAL REPORTS BY NPS CRUSER MEMBERS, FY11 TO PRESENT		110
APPENDIX B: CUMULATIVE THESES AND STUDENT PROJECTS SUPPORTED.....		118
APPENDIX C: COMMUNITY		127
APPENDIX D: CRUSER FY14 CALL FOR PROPOSALS		132
APPENDIX E: CRUSER FY15 CALL FOR PROPOSALS		136
APPENDIX F: CRUSER MANAGEMENT TEAM		142
LIST OF FIGURES		144
LIST OF TABLES		147
LIST OF ACRONYMS AND ABBREVIATIONS		149

EXECUTIVE SUMMARY

From Technical to Ethical...

From Concept Generation to Experimentation...

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems (UxS) education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative designed to build an inclusive community of interest around the application of UxS in naval operations. CRUSER seeks to catalyze these efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, fostering innovation through directed programs of operational experimentation, and supporting the development of an array of educational ventures.

CRUSER captures a broad array of issues related to emerging UxS technologies, and encompassing the successful research, education, and experimentation efforts in UxS currently ongoing at NPS and across the naval enterprise. Controls, sensors, design, architectures, human capital resource requirements, concept generation, risk analysis, cybersecurity, and field experimentation are just a few interest points. In February 2013 the CRUSER community of interest reached the 1,000-member mark, and continues to grow. As a demonstration of CRUSER's relevance and reputation, as of 30 September 2014 the CRUSER community of interest included over 1600 members from government, academia and industry.

In FY14 CRUSER's primary focus was on exploring concepts of interest generated in prior fiscal years. This FY14 Annual Report provides a summary of activities during CRUSER's fourth year of operation and highlights future plans.

I. BACKGROUND

From Technical to Ethical From Concept Generation to Experimentation

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems in military and naval operations

CRUSER encompasses the successful research, education, and experimentation efforts in unmanned systems currently ongoing at NPS and across the naval enterprise. Controls, sensors, design, architectures, human capital resource requirements, concept generation, risk analysis, cybersecurity, and field experimentation are just a few interest points.

Major aligned events starting in FY11 through FY15 are plotted along major program innovation threads (see Figure 1) starting with concept generation workshops, developed in technical symposia, and demonstrated in field experimentation to test selected technologies. These activities each have separate reports, and are available upon request. However, research and education will continue to include a broader landscape than just mission areas.

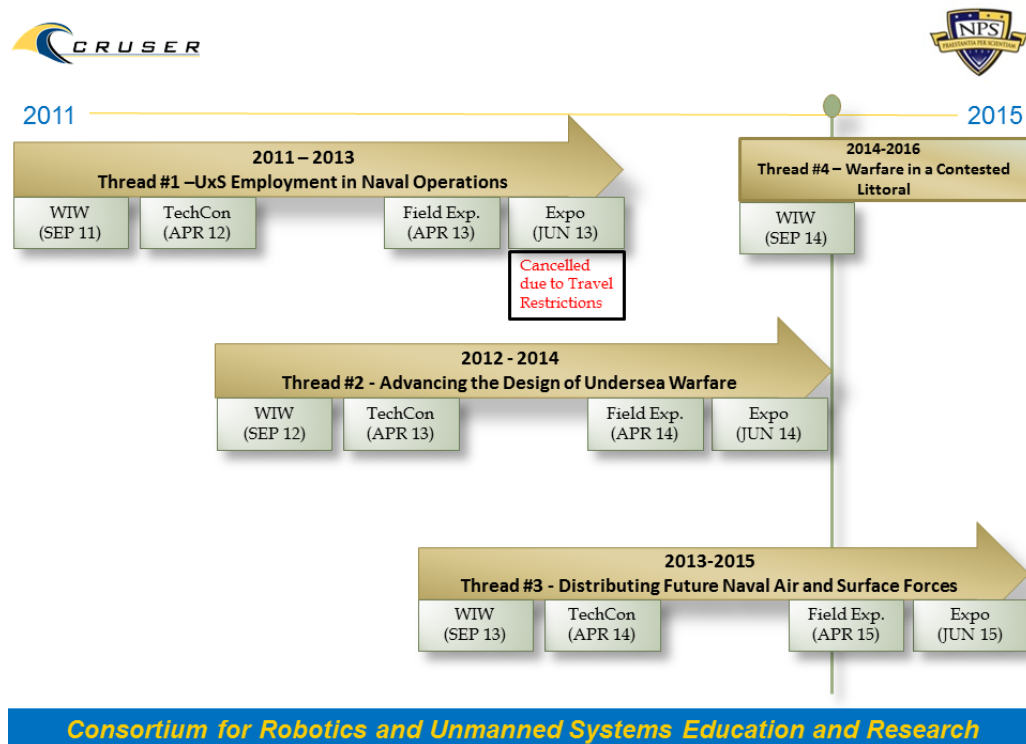


Figure 1. CRUSER program innovation threads as of September 2014

A. VISION

At the direction of SECNAV, NPS leverages its long-standing experience and expertise in the research and education of robotics and unmanned systems to support the Navy's mission. The CRUSER program grew out of the SECNAV's unmanned systems prioritization, and concurrent alignment of unmanned systems research and experimentation at NPS. CRUSER serves as a vehicle by which to align currently disparate research efforts and integrate academic courses across discipline boundaries.

CRUSER is a facilitator for the Navy's common research interests in current and future unmanned systems and robotics. The Consortium, working in partnership with other organizations, will continue to inject a focus on robotics and unmanned systems into existing joint and naval field experiments, exercises, and war games; as well as host specific events, both experimental and educational. The Consortium currently hosts classified and unclassified websites and has established networking and collaborative environments for the community of interest.

Furthermore, with the operational needs of the Navy and the Marine Corps at its core, CRUSER will continue to be an inclusive, active partner for the effective education of future military leaders and decision makers. Refining existing courses of education and designing new academic programs will be an important benefit of CRUSER, making the Consortium a unique and indispensable resource for the Navy and highlighting the educational mission of NPS.

Specific CRUSER goals continue to be:

- Provide a source for unmanned systems employment concepts for operations and technical research;
- Provide an experimentation program to evaluate unmanned system employment concepts;
- Provide a venue for Navy-wide education in unmanned systems;
- Provide a DoD-wide forum for collaborative education, research, and experimentation in unmanned systems.

CRUSER takes a broad systems and holistic approach to address issues related to naval unmanned systems research and employment, from technical to ethical, and concept generation to experimentation. A plethora of research areas inform and augment traditional technical research in unmanned systems, and aid in their integration into fleet operations.

B. MANAGEMENT

CRUSER is organized as a regular NPS research project except with a more extensive charter than most reimbursable projects. It has both an oversight organization and coordination team. The Director, with the support of a lean research and administrative staff, leads CRUSER and executes the collaborative vision for the Consortium. The Director encourages, engages, and enhances on-campus efforts among all four graduate schools and existing centers and institutes. Faculty and students from all curricula with an interest in the development of unmanned systems are encouraged to contribute and participate.

CRUSER continues to build upon existing infrastructure involving research in robotics and unmanned systems, including the Center for Autonomous Vehicles Research (CAVR), and the Center for Network Innovation and Experimentation (CENETIX). These and other programs continue to be major partners in CRUSER research endeavors. The strong interdisciplinary approach of the Consortium is supported by active interest in the Operations Research, Mechanical and Aerospace Engineering, Information and Computer Sciences, Systems Engineering, Electrical and Computer Engineering, Space Systems, Physics, Applied Mathematics, Oceanography, Meteorology, Defense Analysis, and Business Administration Departments at the Naval Postgraduate School. Externally, CRUSER leverages NPS's substantial experience in building collaborative communities to create a dynamic learning environment that engages fleet operators, government experts, industry leaders and academic researchers around the naval unmanned systems challenges.

Courses and educational resources contribute to an integrated academic program. CRUSER augments this holistic academic approach by providing diverse topics and aligned projects for courses not traditionally associated with CRUSER focus areas such as: cost estimation of future systems; data mining large sensor data sets; and manpower and personnel implications of unmanned systems. In FY14, CRUSER also provided funds for supplies and books for ten faculty members who teach UxS related courses across diverse departments.

The Director guides the activities of CRUSER such that they are continually aligned with the unmanned systems priorities of the Navy and Marine Corps. The Director reports to the NPS Dean of Research, and continues to serve as a conduit between associated faculty and students at the Naval Postgraduate School and partnering institutions and agencies.

The Director is supported by an NPS Advisory Committee comprising the NPS Dean of Research, the Undersea Warfare Chair, the Intelligence Chair, the Expeditionary and Mine Warfare Chair, the Assistant Chief of Staff for Aviation Activities, The Senior Information Dominance Officer, the Senior USMC Officer and the NWDC Chair of Warfare Innovation. This committee ensures that the fleet and its operations remain a primary consideration in CRUSER activities to include the selection of research and educational activities funded by CRUSER.

C. FY14 PROGRAM ACTIVITY SUMMARY

The CRUSER FY13 Annual Report concluded with a list of proposed FY14 activities. Now that FY14 is at a close, we have concluded the second innovation thread, are developing the third, and have just begun a fourth thread as planned. Additional progress on planned activities in FY14 included:

- CRUSER hosted a third event in the Robo-Ethics Continuing Education Series to explore legal, social, cultural, and ethical issues for operators, acquisition professionals, and engineers.
- CRUSER hosted a technical gathering called CRUSER Technical Continuum (TechCon) to explore concepts generated the September 2013 Warfare Innovation Workshop (WIW). TechCon 2014 was held on 8-9 April 2014 in conjunction with the annual unmanned systems research fair at NPS.
- CRUSER sponsored experimentation in FY14 of the most promising technologies from TechCon 2013 (April 2013).
- CRUSER had planned to sponsor a technical exposition at ONR in Washington DC to share the results of the CRUSER innovation thread research and experimentation. This event was part of FY14 planning; however, execution was hampered by DoD travel restrictions.
- CRUSER continued to sponsor NPS faculty research and experiments across the holistic topic areas not traditionally sponsored by ONR technical funds such as human resources, human systems integration, concept exploration, and others. The FY15 call for proposals is included as an appendix of this report.
- CRUSER provided a discussion venue for new Navy initiatives. CRUSER also explored an expanded relationship with the Naval Reserve Officers Training Corps (NROTC) Program.
- CRUSER sponsored a WIW in September 2014 to complete FY14, and begin CRUSER Innovation Thread 4.
- CRUSER continued to fund NPS student travel to participate in research, site visits, experimentation, and wargames dealing with all aspects of unmanned systems.
- CRUSER continued to recruit community of interest members, produce monthly newsletters, and hold monthly community-wide meetings.
- CRUSER continued to sponsor and participate in STEM outreach events relevant to robotics education, including NROTC support.

II. PRIORITIES

Concept generation, education, research, experimentation, and outreach are all basic tenets for CRUSER. To support the four CRUSER goals, various activities and research initiatives will occur, ranging from unmanned systems innovation symposia and technical symposia to experimentation and research projects. To support the four CRUSER goals, various activities and research initiatives will occur, ranging from unmanned systems innovation symposia and technical symposia to experimentation and research projects. The six-year funding expectation for CRUSER is:

FY11	FY12	FY13	FY14	FY15	FY16
\$200K *	\$1.4M *	\$2.3M *	\$4.5M *	\$5M	\$5M

** Actual amount received*

Activities for each year are briefed to the Advisory Board and require approval from the sponsor.

FY11 was considered the CRUSER stand up year. With the initial funding, CRUSER was established with a Director, Director for Research and Education, Director of Concept Generation and Innovation, and Operations Manager. A CRUSER Community of Interest was created with over 250 members joining from across DoD, academia, and industry within a month of the creation of the web site (<http://CRUSER.nps.edu>). An information exchange portal (wiki) was created, and monthly newsletter started. CRUSER co-sponsored the Future Unmanned Naval Systems (FUNS) Wargame, and held the first Robots in the Roses Research Fair, as well as several STEM events. CRUSER also supported exploration of UxS as operational decoys, and the Advanced Undersea Weapons Systems (AUWS) Systems Engineering Analysis Capstone Project. A final FY11 Annual Report was released in December 2011 summarizing these activities.

FY12 was CRUSER's first full year in operation and as a transition year, continued many items started in FY11 such as the Community of Interest database, which was over 550 members midway through FY12. The monthly newsletter, monthly VTC meetings, and online presence to include a SIPR site were maintained and expanded. Community-wide monthly meetings were available at NPS, or via VTC or dial-in to allow for collaboration with those are not located at NPS. Funding was provided to eight NPS faculty members to research many aspects of unmanned systems, and included the joint ONR/NPS Seaweb at-sea experimentation program with Singapore. CRUSER sponsored a Warfare Innovation Workshop (WIW) in Naval Unmanned Systems, focusing on revolutionary Concept Generation using evolving technologies. Three teams of NPS students and early career engineers from Navy Labs, academia and industry participated alongside a team with more experienced NPS faculty and engineers from Navy Labs, academia and industry. Five selected focus areas were the basis for presentations that

refined those concepts at the first CRUSER Technical Continuum (TechCon) held in coordination with the Tenth International Mine Warfare Technical Symposium in Monterey, California. Two of the presentations were taken on to experimentation in FY13.

CRUSER continued to provide a discussion venue for new Navy unmanned and robotic initiatives. For example, hosting initial discussions for the Navy's Robotics Education Continuum in conjunction with the CRUSER Technical Continuum provided an opportunity to align unmanned systems education at USNA, NPS and NWC. Additionally CRUSER hosted a Legal, Social, Cultural, and Ethical continuing education seminar for operators, acquisition professionals, and engineers in the Washington D.C. area in coordination with OPNAV N2/6 and ONR.

FY13 saw the completion of the first innovation thread. CRUSER continued many activities from FY11 and FY12 such as the Community of Interest database, which was over 1100 members midway through FY13, a monthly newsletter, monthly VTC meetings, and online presence to include a SIPR site. In FY13 funding was again given to eight NPS faculty members to research many aspects of unmanned systems, and included continued work in the joint ONR/NPS Seaweb at-sea experimentation program with Singapore. CRUSER sponsored four midshipmen from USNA to complete summer internships in various labs. CRUSER held the second event in the Robo-Ethics continuing education series for operators, acquisition professionals, and engineers in September 2013 to continue the discussion begun during the January 2012 event held in Washington DC. Community-wide monthly meetings continued to be available at NPS, or via VTC or dial-in to allow for collaboration with those are not located at NPS. CRUSER sponsored two Warfare Innovation Workshops (WIW) during FY13 focusing on the second innovation thread: Advancing the Design of Undersea Warfare. Teams of NPS students and early career engineers from Navy Labs academia and industry presented over 40 concepts. Seven selected focus areas were the basis of presentations at the NPS CRUSER Technical Continuum (TechCon) held in April 2013. From those two days of presentations, four of the presentations were funded for experimentation in FY14.

FY14 was the first year at full funding and execution. CRUSER continued many items started in previous years such as the Community of Interest database, which hit over 1,300 members midway through FY14. The monthly newsletter, monthly VTC meetings, and an expanded and improved online presence are program activities that will continue to mature. Community-wide monthly meetings are available at NPS, via VTC, via Elluminate, or dial-in to allow for collaboration with those who are not located at NPS. CRUSER sponsored a Warfare Innovation Workshops (WIW) during FY14 focusing on our third innovation thread: Distributing Future Naval Air and Surface Forces. Four teams of NPS students and early career engineers from Navy Labs, academia and industry generated many innovative concepts. Selected focus areas from the WIW were refined at the NPS CRUSER TechCon 2014 held in April. From those two days of presentations, it is anticipated that several of the presentations will be funded for experimentation in FY15.

The fourth annual Robots in the Roses Research Fair was the concluding event of the annual TechCon in April 2014. This event provides an opportunity for NPS Faculty and NPS Students

to showcase their research, STEM activities for K-12 children, and allows the NPS community at large to learn more about unmanned systems and robotics. In May 2014, CRUSER held two panels at the Navy-sponsored Eleventh International Mine Warfare Technology Symposium and also hosted a TechExpo in conjunction with the symposium on the final day. The TechExpo allowed symposium participants to participate in a poster session showcasing the work of NPS faculty and students, and offered lab tours of various unmanned systems or robotics labs across NPS.

Funding in FY14 was granted to just over 20 NPS faculty members to study many diverse aspects of unmanned systems including increasing education opportunities in addition to research. CRUSER also funded 23 NPS students to travel in FY14 to participate in research, and experimentation dealing with all aspects of unmanned systems to help develop the next generation of military officers.

Specific FY14 objectives were to provide:

- an education venue,
- a source of concept generation,
- DoD-wide experimentation programs,
- and a DoD-wide forum for collaboration

The remaining sections of this report will address each of these objectives.

A. EDUCATION

CRUSER education programs consist primarily of science, technology, engineering, and math (STEM) outreach events; support for NPS student thesis work; and a variety of education initiatives. These initiatives include sponsored symposia, catalog degree programs, short courses, and certificate programs. CRUSER's education work also involves surveying and aligning curricula for interdisciplinary unmanned systems education. In keeping with its mandate to include other DoD entities in the COI CRUSER sponsored two students from U.S. military academies, one from USAFA and one from USMA, to complete summer internships in various NPS labs. In March 2014 CRUSER held the third installment in its Robo-Ethics Continuing Education Series in San Diego with VTC connections to NPS, the Pentagon, USNA, and NSWC-Panama City.

1. Education Projects

In September 2013, CRUSER made its second call for proposals to seed education topics. CRUSER gave seed money to several projects in FY14 with deliverables primarily focused on education (*see Table 1*). The stated funding period was 31 October 2013 through December

2014, and the funding levels were set at \$75,000 to \$125,000 per proposal. Due at the beginning of September 2013, ten proposals totaling nearly \$1 million in requests were considered for CRUSER funding. The CRUSER advisory committee selected six projects, and granted just over \$500 thousand in total to support their work in FY14.

Table 1. FY14 CRUSER funded projects for curriculum development (alphabetized by Principal Investigator last name)

PRINCIPAL INVESTIGATOR(S)	PROJECT TITLE
Dobrokhodov, Du Toit	An Integrated Indoor Unmanned System Experimentation Facility for Campus-wide Teaching and Research
Harkins	A Student built Autonomous Ground Vehicle as a Course Project for the Benefit of the CRUSER Community
Giammarco	A Manual for the Model-Based Design and Assessment of Robotics and Unmanned Systems
Joseph, J	Glider applications in Tactical Oceanography
Kaminer, Jones, Dobrokhodov	Defense against Swarms: A Key Naval Capability
Kamel	Introduction to Big Data and Analytics Course Development

As the period of performance ends on 31 December 2014, all CRUSER funded projects are in various stages of completion at this report date of 30 September. These research summaries are listed in alphabetical order by primary Principal Investigator (PI) last name, and each project includes a POC listed for further inquiry.

a. An Integrated Indoor Unmanned System Experimentation Facility for Campus-wide Teaching and Research

The ongoing project focuses on the development and integration of new user-friendly capabilities within the hardware and software settings provided by the VICON indoor positioning system and advanced modeling and simulation capabilities developed by the MatLab/Simulink and ROS research communities. There are two sub goals in this project – instrumentation and education. The end-goal of the instrumentation portion of the project is to develop a “Common Operational Environment” for robotics experimentation that would maximize the effective instrumented use of the available operational volume, (see Figure 2). The idea of the educational portion of the project is to develop and implement in the VICON environment a number of software algorithms which are fundamental to the Unmanned Systems Curriculum (USC); USC is comprised of classes currently taught in GSEAS by various departments, including MAE, ECE, EE, SE, and Physics. The immediate benefit provided by the results of this effort is in bridging the gap between learning the theoretical concepts and implementing the novel concepts in real indoor experimental facility in “no-time.” When completed, this effort will establish a base integration framework (both hardware and software) that will contribute to a number of current and future educational and research efforts of the NPS robotics community.

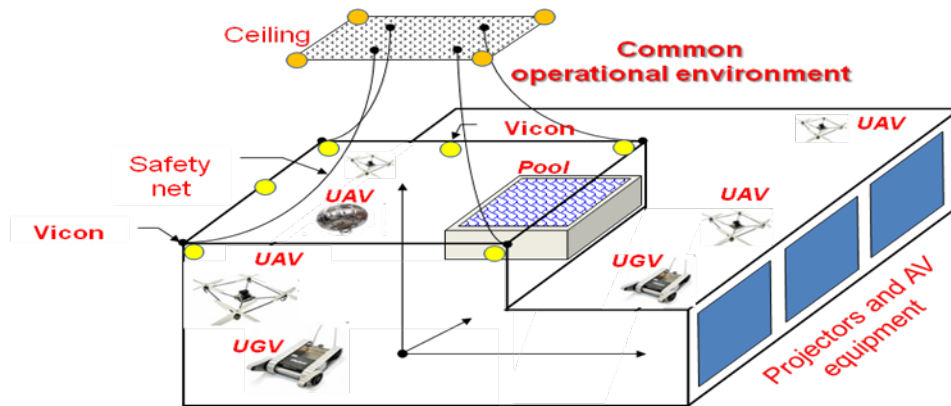


Figure 2. Common Operational Environment

The difficulty of comprehending abstract mathematical concepts that are widely used in engineering is often underestimated. The proposed effort aims to make the theory *accessible* and *intuitive*, thereby *enabling* students to fully utilize its potential and *evolve* to more advanced levels quickly. This is especially true for the military students coming to NPS for very dense two-year residential programs. The ultimate objective of the proposal is to *bridge the gap between the theoretical content of class material and the practical understanding* of steps involved in the design and implementation of the robotics algorithms and their *experimental validation and verification*. The *objective will be achieved* by developing (i) logical, streamlined experimental procedures, (ii) user-friendly software interfaces, and (iii) a convenient and forgiving hardware experimental environment. The students' *progress will be assessed* by the performance of robots autonomously navigating in the VICON-based indoor experimental environment.

The *innovation* of the proposed work is threefold. First, the framework will enable the NPS resident students to experience the excitement of controlling operationally relevant autonomous platforms at will. Second, the framework will enable competitive and collaborative advancement of current and future courses in the autonomous systems curriculum. Third, since the same setup is extensively used in externally funded projects (NASA, ONR, AFRL, etc.), the students will be well-prepared for the thesis work in the same facility no matter what department sponsors their thesis work in the general field of autonomous robotics.

Therefore, software development is primarily focused on advancing the educational impact of modern concepts in robotics and unmanned systems by providing a student-friendly and forgiving means of experimentation with highly integrated autonomous robots. Focusing on a specific course allows the proposers to identify relevant capabilities and learning outcomes, which are motivated more generally by campus-wide research and educational needs. Thus, the effort focuses on the development of procedural materials that effectively introduces students to the facility and capabilities as part of their education and in preparation for thesis research. Materials developed will significantly contribute to a number of disciplines taught across campus in support of USC and other programs. The proposed effort will leverage the results of numerous

research projects performed by the faculty and students in CRUSER, thus bringing the latest advancements of the research into classroom environment.

The advanced computer modeling and design tools provided by MathWorks (e.g., MATLAB/Simulink and the robotics/vision oriented toolboxes) is the *de facto* algorithm development environment in the unmanned systems community. Similarly, the Robot Operating System (ROS) has become the *de facto* embedded execution environment for robotic systems. ROS is a large-scale open-source effort aimed at facilitating and standardizing the development and deployment of complex robotics systems, thereby ensuring cross-platform compatibility and capability reuse. Exposing students to these standardized approaches allows them to apply skills and knowledge acquired in various classes to a variety of robotic platforms, ranging from underwater systems to ground/surface and aerial platforms. As a result, students are better prepared to transition knowledge and skills from the classroom to their thesis work. Furthermore, since ROS is the foremost execution environment that captures the state-of-the-art in robotic mission execution, it is imperative to expose the students to this framework.

Thus, based on our extensive R&D experience, leveraging the well-instrumented CAVR laboratory facility and utilizing the advanced software tools that are already used for teaching and research, we are integrating the capabilities of VICON motion capture system with a combined MATLAB and ROS-based software-hardware framework that is well-suitable for teaching (e.g., rapid control system design, hardware-in-the-loop (HIL) simulation and in-flight validation and verification) as part of the courses listed above. Specifically, we are developing a set of laboratories (description of theory and the experimental procedures) based on the MATLAB development and ROS execution environments in support of ME4821, using robots available at NPS. The sequence of laboratories for ME4821 follows the corresponding chapters of the navigation class and includes the following experimental sections:

- Lab. Assignment 1. Introduction to the *ROS execution environment* and its integration with *VICON* hardware setup; accessing data from VICON communication interfaces => **Completed.**
- Lab. Assignment 2. Introduction to the *Simulink modeling environment* and its integration with *VICON* hardware setup; accessing data from VICON communication interfaces => **Completed.**
- Lab. Assignment 3. *Navigation* - algorithms for the navigation states' estimation and filtering. Basics of integrating "Range Only Measurements" => **Completed.**
- Lab. Assignment 4. *Perception* - the principles of inertial measurements and sensors including accelerometers, rate gyros, pressure transducers, altimeters, GPS system => **50%.**
- Lab. Assignment 5. Advanced Navigation - *INS/GPS integrated* solutions and modern autopilots => **25%.**
- Lab. Assignment 6. *Guidance* - algorithms for path planning in an uncertain, unknown environment=> **50%.**
- Lab. Assignment 7. Control algorithms that solve the *path following* problem => **10%.**
- Lab. Assignment 8. *Communication* – key enabler of cooperative capabilities => **10%.**

Central to the experimental setup is the use of off-the-shelf technology, thus exploiting the economy of scale of a number of commercial products. The architecture emphasizes high-level

algorithm design utilizing MatLab/Simulink as a design platform. Low-level code and hardware driver generation is therefore kept to a minimum, with the vast majority of the code “writing” being done via auto-coding tools provided by the MathWorks’ Embedded Coder. Major benefits of the proposed architecture include:

- Convenience of high-level algorithm design, auto-coding capabilities and hard real-time execution support from MathWorks (this allows the students to rapidly augment algorithms);
- A uniform execution and deployment environment that allows extension and utilization in thesis work;
- High-reliability of payloads built on industrial grade PC104 boards and miniature sensors and actuators;
- Simple and transparent interfacing to hardware that is primarily based on the community developed and maintained driver interfaces as part of the ROS execution environment;
- Reliable telemetry links are self-contained, providing auto configuring and discovery capabilities over secure protocols.

Finally, the effort leverages research funds already secured for a number of projects currently led by CRUSER faculty. In particular, the Unmanned Aerial Systems group will invest funds available from NASA “Mitigation of Adverse Effects of Loss of Communication Link on Cooperative UAV flight in NAS” and ONR “Coordinated ISR by a Team of Heterogeneous UAVs” projects. Moreover, the NPS Undersea Warfare Curriculum has been very supportive of the effort to acquire the positioning system in support of CAVR’s vision of creating a world-class research and educational facility.

POC: Dr. Vlad Dobrokhodov (vndobrok@nps.edu) and Dr. Noel DuToit (nedutoit@nps.edu)

b. A Student built Autonomous Ground Vehicle as a Course Project for the Benefit of the CRUSER Community

This is a sponsored **educational** grant. The *primary objective* is to execute a course project where students build, test and deploy a ROS enabled autonomous ground vehicle for the benefit of NPS CRUSER.

A *secondary objective* is to expose students to the difficulty of taking “chalkboard” knowledge to the reality of an actual “autonomous platform”. The project was awarded in May of 2014 with a period of performance that expires in December of 2014.

Research and Design Methodology:

Execution of the project is phased in three steps:

Step one: (*Complete*)

It began in May of 2014 and included the ***planning phase*** for the research. Here, twelve students were selected to participate in the project. Hardware and software requirements were identified for purchase. (Parts orders continue to date in support of the platform build.) A *Needs Requirement Document* was established as a governing directive for the project.

It was determined that the sensor suite would include Hokuyo laser rangefinders, and an array of acoustic sensors for operational space mapping and obstacle avoidance. To support thermal detection, a thermopile array was identified for use. Maxon motors were specified and will be driven by a Roboteq motor controller.

The micro-controller was down-selected to a Raspberry Pi with a mini-portable, Linux computer, purchased, and set aside as a backup.

A Roboteq RIO daughter board was selected for use as the interface to the Raspberry Pi and to the Arduino Micro-controller. The RIO has interfaces for analog and digital and serial IO. It also has rate gyros and accelerometers for positional awareness and dead reckoning. The Arduino micro-controller is used to drive all the sensors via an I2C bus.

The Robot Operating System (ROS) is used to program the autonomous vehicle.

Step two: (*In progress*)

This step began in June of 2014 and includes the course and ***build phase*** for the project. Weekly contact hours have been set aside for a 12-week build and this scheduled to be complete by September 28 2014.

Course work exposes the students to a variety of topics including:

- Historical Perspective
- Robotic operational paradigms
- Lagrangian Robot Dynamics
- Autonomy
- Micro-controllers, Sensors and Actuators
- Control
- Algorithms
- Robot Operating System

Students are separated into three teams: (1) Hardware, (2) Software and (3) Sensors.

Hardware: The hardware platform has been designed in CAD (*see Figure 3*) with many parts still to be printed via 3D printing techniques. Figure 2, shows a close up view on the track roller to be 3D printed. The platform is in the build process.

The power bus will be implemented on a primary 48-volt bus with regulators for 15, 12 and 5-volt loads. The power budget has been established with predictions of 1.5 hours on-station-time between charges for normal operations.

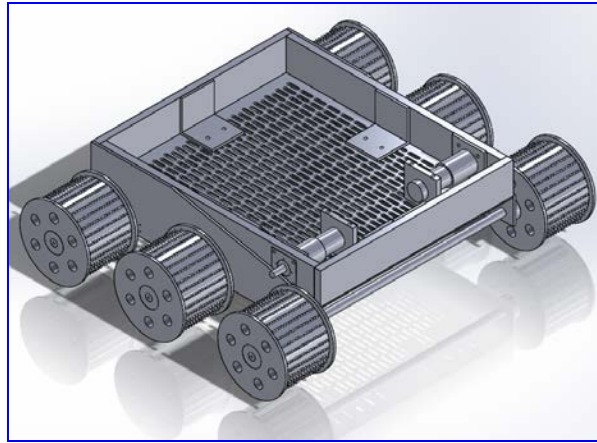


Figure 3. Student designed CAD rendering of the vehicle.

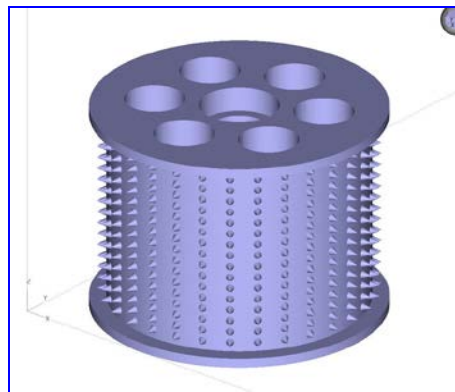


Figure 4. Robot Track Roller

Sensors: Sensor packages have been bench-tested and the majority of drivers have been written to support IO requirements. The Hokuyo Laser Ranger has been successfully tested in the lab under ROS.

Software: Software drivers for the Sensors (Acoustic, Thermal and IR) are written and run off of an I2C bus via the Arduino Micro-controller. The main algorithm for robot-control has been established (*see Figure 5*):

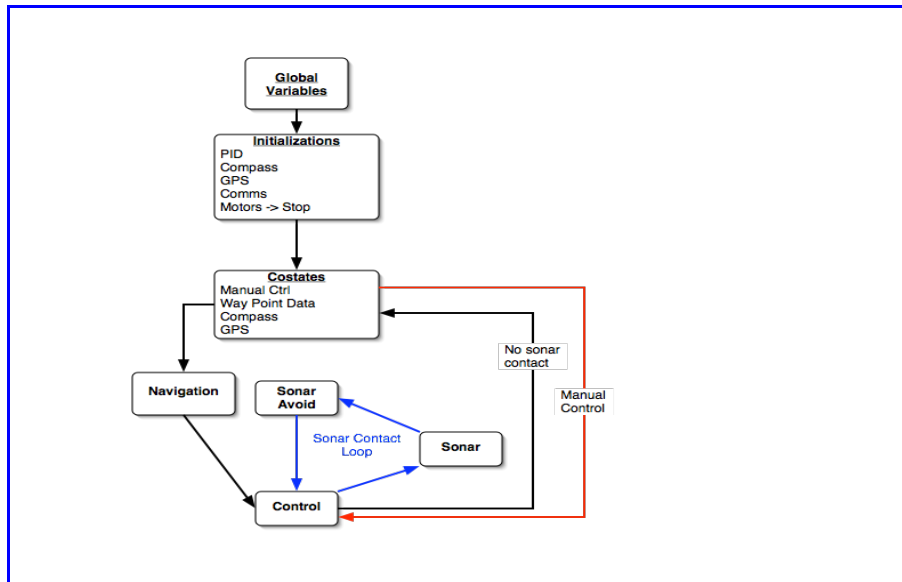


Figure 5. Autonomy Algorithm

Work on a user interface for remote management and the testing of a wireless communications package, has not started. This will be delayed to step three.

Step Three: *(not yet started as of 30 September 2014)*

This Phase begins 01 October 2014 and includes the **integration, testing and delivery** phase. It will include faculty and student interaction as a directed study as the robot is tested and deployed against the Needs Requirement Document.

During integration and testing; hardware, sensors, communication and software will be vetted for performance in various operational settings including: (1) Urban internal building recon and surveillance and (2) Outside, GPS enabled waypoint navigation and obstacle avoidance scenarios.

Analysis and Results

This project is still in the build phase. Results and analysis is therefore deferred to the next quarterly report.

Projections

We expect this project to be successfully completed within the time constraints of the period of performance.

POC: Richard M. Harkins (rharkins@nps.edu)

c. Introduction to Big Data and Analytics Course Development

The organization, management and analysis of intelligence data is a major and fast growing concern for DoD. Data is being collected at exponential rates from a variety of sources such as satellites, Unmanned Aerial Vehicles (UAVs), and higher-definition sensors installed on surveillance aircrafts. These machine-generated data, referred to as Big Data, reflect datasets that are so large that it is beyond the ability of conventional hardware and software technology to effectively capture, store, manage, and analyze.

Hundreds of hours of sensor data streams per flight generated by each Unmanned Aerial Vehicle (UAV) or Wide Area Surveillance system. All this sensor data can be invaluable to the warfighter, but the challenge is to store, organize, and analyze it to produce actionable information in a timely manner. As an example, the Defense Advanced Research Projects Agency's (DARPA) Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System (ARGUS-IS) is the equivalent of 60 to 100 Predator UAVs looking at a particular area simultaneously. It uses 368 five Megapixel detectors capable of generating more than 260 Giga bits per second of raw data. This means that these sensors are expected to produce 1000x more information just in the next few years.

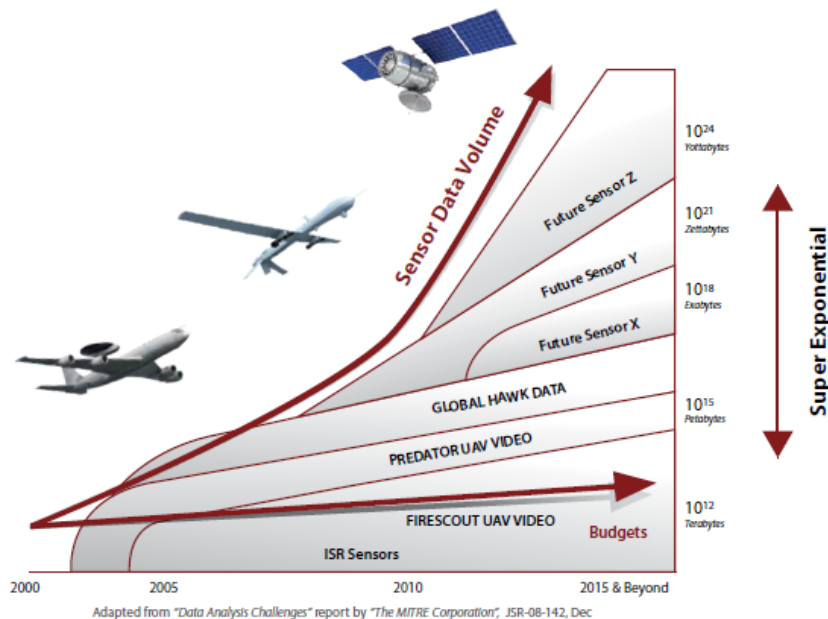


Figure 6. Super exponential growth in big data

The challenge of Big Data is that the datasets collected are so large that it becomes difficult to, store, organize, search, share and analyze the data within a reasonable period of time. The inability to store and analyze this data to identify relevant intelligence can lead to missed opportunities to find insights into new and emerging kinds of threats, and provide rapid, real-time decision support to the right people, in the right place, at the right time.

New approaches are being developed aimed at organizing, storing, exploring, processing, visualizing, and analyzing these very large data sets. However, there is an acute shortage of analysts or “data scientists” who understand the concepts of Big Data and how to mine through these large sets of data streams. DoD is in competition with private industry as these scientists are sought out throughout the commercial industry.

Objective

The objective of this project is to develop an introductory course in Big Data and Analytics to provide military officers a thorough understanding of the tools, methods, applications and practice of Big Data and advanced analytics from a military decision making perspective. Students learn how to influence military decision-making, strategy and operations through organizing, exploring, visualizing, processing and analyzing very large data sets. The proposed course integrates topics in data management, analytics, and visualization with military operations to give students a good understanding of how data analysis drives military decision making.

Main Course Topics

1. Introduction: What is meant by “Big Data” and what special problems does it represent for storing, organizing, and analyzing sensor data
2. Acquiring Big Data: Satellites, Unmanned Aerial Vehicles (UAVs), high definition sensors, geographical databases APIs, social media and online databases APIs
3. Scalable Data Management: relational and NoSQL databases, parallel and distributed databases, Hadoop, HDFS, Hbase, Hive and Pig, MapReduce, data preparation and cleaning
4. Analytics: Statistical Modeling, experimental design, Bayesian Decision Theory and Naïve Bayes, Regression, decision trees/forests, k-nearest Neighbors, Clustering , k-means, machine learning, supervised learning, unsupervised learning, Neural Networks, support vector machines, principal component analysis, graph analytics, text analysis, and natural language processing
5. Communicating the Results: Visualization, and visual data analytics

Deliverables

- i. Course Syllabus
- ii. Annotated PowerPoint Presentations

- iii. Class Notes
- iv. Class/Lab Exercises
- v. Readings Lists

POC: Professor Magdi Kamel (mnkamel@nps.edu)

d. A Manual for the Model-Based Design and Assessment of Robotics and Unmanned Systems

This project aims to increase knowledge and skills in early lifecycle architecture design and assessment of robotics and unmanned systems. This objective is being accomplished through the writing of a multidisciplinary manual for use in courses, design projects, theses, capstone projects and/or research projects. The manual will provide a running case study example throughout the chapters centered around a Search and Rescue (SAR) operational scenario to illustrate general architecting concepts that may be applied in any scenario. SAR was selected as the operational context for several reasons:

- a global concern that applies in both DoD and commercial / civilian applications,
- the anticipated ease of collecting releasable data on SAR scenarios, and
- the large range of scopes in which specific problems can be framed, from tradeoff analyses of one robot's subcomponents through planning and assessment of entire Systems of Systems (SoS) of unmanned platforms.

An example high level analysis question that architectural analysis can support is the following: "How would the employment of robotics and unmanned systems impact the execution of SAR missions?" (Alternatively, other kinds of missions may be substituted for SAR.) The systems engineer must work with the stakeholder(s) to decompose a high level question such as this one into more precise questions that are answerable by an analysis framework. For example, specific objectives may be to decrease time to locate victims, time to execute the rescue once located, risk to first responders, or lifecycle cost; and/or to increase probability of detection, search area coverage, or victim survivability. The manual shows its users how to reason about such questions using an architecture modeling approach and state of the practice methods, tools, and notations capable of modeling architectural properties of robotics and unmanned systems.

The current manual outline is as follows:

Chapter 1: A Search and Rescue (SAR) Design Reference Mission (DRM)

Chapter 2: Operational Scenarios for SAR

Chapter 3: Model Execution: Simulation of SAR Operational Scenarios

Chapter 4: Creating Solution-Neutral Architecture Views

Chapter 5: Concept Generation and Selection of Top Candidate Solutions

Chapter 6: Creating Solution-Oriented Views: Narratives & Sequence Diagrams

Chapter 7: Creating Solution-Oriented Views: Activity & Behavior Diagrams

Chapter 8: Model Execution: Simulation Analysis of Alternatives

Chapter 9: Requirements Generation and Traceability

Chapter 10: Presenting the Architecture Model and Analysis Results to Stakeholders

In addition to presenting the general architecture modeling concepts, exercises in the form of lab assignments are being developed near the end of each chapter to allow learners to put the concepts into practice. Criteria for self- and instructor assessment are also to be provided.

POC: Dr. Kristin Giammarco (kmgiamma@nps.edu)

2. Education Initiatives

The CRUSER Technical Continuum (TechCon) 2014 and the 4th Annual Robots in the Roses research fair again led the CRUSER education efforts in FY14. Education initiatives in FY14 also included the third event in the CRUSER Robo-Ethics Continuing Education Series, and sponsorship of several internships at NPS.

a. Continuing Education: Robo-Ethics, March 2014



This third event in the full Robo-Ethics Continuing Education Series was held on the afternoon of 24 March 2014. A select panel of subject matter experts was assembled in the TACTRAGRU auditorium in San Diego to give input to a commander responding to a potential future operational scenario. The Commander, a role filled by RADM Peg Klein, attended the event by teleconference from The Pentagon. The panel of advisors was broadcast live from San Diego,

and the audience of junior officers was attending from a variety of sites throughout the U.S. The panel of advisors consisted of:

- The Roboticist: Dr. Timothy Chung, NPS
- The Industry Expert: Dr. Rand LeBouvier, Bluefin Robotics
- The Operator: CAPT Bob Shultz, USN (ret.)
- The Lawyer: CDR Shane Cooper, USN THIRD FLEET
- The Philosopher: Dr. Bradley Strawser, NPS
- The Future Commander: LT Benjamin Elzner, NPS

Panelists were asked to envision a futuristic scenario where an escalating series of events leads to war. Newly-appointed Senior Advisor for Military Professionalism Rear Adm. Peg Klein participated via VTC from Washington, D.C. Klein was asked to weigh the need to deploy unmanned and manned systems during the notional crisis, while audience members also weighed in and contributed questions and insights into the scenario.

“The diversity of backgrounds, experiences and disciplines on the panel was great ... Having that breadth of insight across channels was an excellent way to convey the many difficulties and ethical conundrums a future commander will face with this newly-emerging technology,” said Strawser.



Figure 7. A diverse panel of leading thinkers in the field of ethics and robotic systems, led by NPS Department of Defense Analysis Assistant Professor Dr. Bradley Strawser, shown above center, participates in the Robo-Ethics 2014 event in San Diego CA (24 March 2014).

Strawser, who has written extensively on the ethical implications of unmanned systems, discussed the continuing need to debate morality in relation to robotic systems. “The future of robotics technology and unmanned systems complicates the moral decisions future commanders will have to make on several orders of magnitude. Asking these tough questions today, will help prepare our future leaders tomorrow,” said Strawser.¹

¹ Adapted from NPS Photo News, 25 March 2014 “Robo Ethics 2014 Takes the Debate to the Naval Commander,” Javier Chagoya. NPS Photo News items are published daily by the Naval Postgraduate School's Public Affairs Office. For additional information, comments or suggestions, please contact pao@nps.edu



Figure 8. NPS students attending Robo-Ethics 2014 via VTC from the NPS campus in Monterey CA

In light of DoD travel restrictions, CRUSER arranged to have the panel discussion available via video teleconference (VTC) for audiences of operators at several locations (see Table 2).

Table 2. Robo-Ethics 2014 event attendance

TACTRAGRUPAC San Diego CA	40
NPS Monterey CA	11
USNA Annapolis MD	8
NSWC Panama City FL	5
Voice only participants	9
TOTAL:	73

CRUSER also offered a voice-only option for those who wanted to participate, but did not have VTC capability available to them at their location.

b. CRUSER Scholars and STEM Outreach

Eleven CRUSER faculty members hosted graduate, undergraduate and high school level interns at NPS during 2014. Students studied alongside NPS faculty in UxS related fields of computer science, human systems integration, mechanical and aerospace engineering, oceanography, operations research, signals intelligence, and systems engineering.

The Advanced Robotic Systems Engineering Laboratory (ARSENL) represents a diverse academic and research group at the Naval Postgraduate School, emphasizing that robotic and unmanned systems merit a holistic, multi-disciplinary approach for their design, their employment, and their future concepts. ARSENL had a total of nine summer 2014 interns. The interns' backgrounds ranged from high school to graduate level educations. Two interns were Cadets from USMA and USAFA. One intern studied the feasibility of landing 50 UAVs in 15 x 15 meter box in under a minute. Another intern explored how to implement a simple Boids

algorithm while keeping the onboard autonomy (using Robot Operating System (ROS)) and ground control station (using MAVProxy) architectures in mind. Joystick control of a UAV was the focus of another intern. Distributed algorithms for the Aerial Combat Swarms competition was the area of study for our interns.

3. NPS Course Offerings and Class Projects

Select NPS courses contribute to CRUSER's mission by conducting class projects in various aspects of unmanned systems employment. Unmanned systems are studied directly, or introduced as a technical inject for use in strategic planning or war gaming. Beyond advancing research and concept development, these projects enhance education in unmanned systems.

a. Systems Engineering Analysis (SEA) 20, 2014

Sponsored by the CNO Warfare Integration Division Chair of Systems Engineering Analysis, this inter-disciplinary curriculum provides a foundation in systems thinking, technology and operations analysis for warfighters. Each cohort must produce a report detailing their research, and make a recommendation based on their findings. Two cohorts, SEA20A and SEA20B, were tasked by OPNAV N9I to explore distributed surface and air wing capabilities in the challenging anti-access, area-denial environments.

SEA20A: U.S. and Singaporean military officers and Singaporean defense industry civilians explored the design of a Distributed Surface Force in the 2025-2030 timeframe. Using a uniquely tailored systems engineering approach, their study recommends a 1500 ton surface combatant to augment small surface combatants for littoral missions - including power projection, sea lines of communication patrol, and deterrence through presence. The distributed force architecture was designed to be scalable from a small compliment of U.S. ships to a multi-nation armada, and then to a blue-water carrier group. A key driver in the analysis was the \$500 million acquisition budget and 10-yr operating costs at half the acquisition costs for organic sensors capable of detecting and classifying targets at 100km range, anti-surface warfare missions capable of firing 150km, and full operations within an environment of anti-access area denial. SEA20B, charged with exploring a Distributed Air Wing Concept, was comprised of a diverse team of U.S., Singaporean, Israeli, and Taiwanese students engaged in cross-campus academic disciplines. Through the course of their work they found that the development of advanced anti-access/area denial (A2AD) threats by potential adversaries presents a significant challenge to the United States Navy. The proliferation of these threats makes operating an aircraft carrier from contested waters an extremely risky endeavor. If a carrier must be withheld from the battle or is put out of action, the entire capability of the air wing is lost.

SEA20B: The Systems Engineering process was applied to this problem by exploring a concept called the "Distributed Air Wing (DAW)." This high level concept includes various methods to distribute and disperse naval air capabilities from their centralized location on an aircraft carrier. Their study outlined the development and analysis of three conceptual designs that fall under the concept of the DAW; a dispersed land and sea basing concept that utilizes carrier borne Navy

and Marine Corps aircraft (Dispersed Air Wing Operations), a seaborne unmanned aircraft courier system (Sea Scout), and a carrier based unmanned air-to-air vehicle (MTX). The analysis in their final report demonstrates that a mixture of these alternatives in varying degrees will deliver the fleet's three most critical capabilities, ISR, Offensive/Defensive Counter Air, and Surface/Land Strike, with less risk than the current CVN/CVW force structure and operational doctrine.

POCs: Dr. Gary Langford (golangfo@nps.edu) and Dr. Timothy Chung (thchung@nps.edu)

b. Search Theory and Detection (OA3602), Spring 2014

Students in this course, Search Theory and Detection (OA3602) investigated the mathematical and computational foundations of applied probability, stochastic systems, and optimization modeling in relation to operationally relevant search scenarios, such as anti-submarine warfare, mine clearance and sweeping, and combat search and rescue. Such mission sets, to also include intelligence, surveillance, and reconnaissance (ISR); harbor security; and border patrol, are increasingly involving unmanned systems. Students from Operations Analysis and Undersea Warfare curricula engaged in exercises in mathematical modeling as well as group projects which enabled advanced applications of such technical injects such as operational unmanned aerial systems or future concept capabilities (such as DARPA Hydra).

POC: Dr. Timothy H. Chung (thchung@nps.edu)

c. Joint Campaign Analysis (OA4602), Winter and Summer 2014

The Joint Campaign Analysis course is an applied analytical capstone seminar attended by operations research students, joint operational logistics students, modeling and simulation students, and systems engineering analysis students. It uses scenarios and case studies for officers to use the skills they have acquired in their degree programs in an operational environment. In a South China Sea, Strait of Hormuz, and Baltic scenario students were asked to explore the requirements for and capability gaps in maritime ISR and expeditionary operations to conduct covert mine warfare and Marine Corps raiding capability.

POC: Professor Jeff Kline (jekline@nps.edu)

d. Advanced Applied Physics Lab (PC4015), Winter and Summer 2014

Students incorporate knowledge of analog and digital electronic systems to design, implement, deploy and demonstrate an autonomous vehicle. The vehicle is required to demonstrate navigation and collision avoidance. The course is taught in a standard 12-week format. A Needs

Requirement Document is presented. Design reviews are held at the 4 and 8 week period. Demonstration of Autonomy is required to pass the class.

POC: Professor Richard M. Harkins (rharkins@nps.edu)

e. Policies and Problems in C4I (CC4913), Spring 2014

Students in this course study the fundamental role C2 systems fulfill in operational military situations, including the full range of military operations. Analysis of the changing role of organizational structures and processes as well as technologies and impacts on C2 systems requirements and designs is central to the curriculum. Students in this course are asked to consider the complexities imposed on C2 systems as the force structure becomes more heterogeneous, as in the case of NATO and NGOs. Case studies of selected incidents and systems focus on current problems.

POC: Dr. Dan Boger (dboger@nps.edu)

4. NPS Student Theses

The primary mission of NPS is to educate members of the U.S. armed forces. CRUSER community of interest members guided several NPS students as they developed and completed their thesis work throughout the CRUSER program lifetime (*included in a cumulative listing in Appendix B*). The following table (*see Table 3*) lists students mentored in FY14, as well as those who graduated in September 2013 as their thesis work was still in academic processing when the FY13 CRUSER report was released.

Table 3. FY14 CRUSER mentored NPS student theses (*alphabetical by student*)

Thesis project title/subject:	NPS Student(s)	
<i>Applying Cooperative Localization to Swarm UAVs using an Extended Kalman Filter</i>	Lieutenant Colonel Robert B. Davis, USMC	FY14 (SEP)
<i>Expanded Kill Chain Analysis of Manned-Unmanned Teaming for Future Strike Operations</i>	Joong Yang Lee, Republic of Singapore Air Force	FY14 (SEP)
<i>Logistics Supply of the Distributed Air Wing</i>	Mr. Chee Siong Ong, Singapore Defence Science and Technology Agency	FY14 (SEP)
<i>Assessment of Vision-Based Target Detection and Classification Solutions Using an Indoor Aerial Robot</i>	LT Nicole Ramos, USN	FY14 (SEP)
<i>Optimal Estimation of Glider's Underwater</i>	JooEon Shim	FY14

<i>Trajectory with Depth-dependent Correction using the Regional Navy Coastal Ocean Model with Application to ASW</i>		(SEP)
<i>Relationship between the sonic layer depth and mixed layer depth identified from underwater glider with application to ASW</i>	LT Vance Villarreal, USN	FY14 (SEP)
<i>] A Modular Simulation Framework for Assessing Swarm Search Models</i>	LT Blake Wanier, USN	FY14 (SEP)
<i>The distributed air wing</i>	Systems Engineering Analysis Cross-Campus Study (SEA 20B)	FY14
<i>Sea-Shore interface robotic design</i>	LT Timothy L. Bell, USN	FY14
<i>Achieving information superiority using hastily formed networks and emerging technologies for the Royal Thai Armed Forces counterinsurgency operations in Southern Thailand</i>	LCDR Anthony A. Bumatay, USN; LT Grant Graeber, USN	FY14
<i>Droning on: American strategic myopia toward unmanned aerial systems</i>	CWO4 Carlos S. Cabello, USA	FY14
<i>Obstacle detection and avoidance on a mobile robotic platform using active depth sensing</i>	ENS Taylor K. Calibo, USN	FY14
<i>Improving operational effectiveness of Tactical Long Endurance Unmanned Aerial Systems (TALEUAS) by utilizing solar power</i>	LT Nahum Camacho, Mexican Navy	FY14
<i>Increasing the endurance and payload capacity of unmanned aerial vehicles with thin-film photovoltaics</i>	Capt Seamus B. Carey, USMC	FY14
<i>Power transfer efficiency of mutually coupled coils in an aluminum AUV hull</i>	LCDR James M. Cena, USN	FY14
<i>Tropical cyclone reconnaissance with the Global Hawk: operational thresholds and characteristics of convective systems over the tropical Western North Pacific</i>	LCDR David W. Damron, USN	FY14
<i>Cost-effectiveness analysis of aerial platforms and suitable communication payloads</i>	LCDR Randall E. Everly, USN; LT David C. Limmer, USN	FY14

<u>Characterization parameters for a three degree of freedom mobile robot</u>	LT Jessica L. Fitzgerald, USN	FY14
<u>Computer-aided detection of rapid, overt, airborne, reconnaissance data with the capability of removing oceanic noises</u>	LT James R. Fritz, USN	FY14
<u>A data-driven framework for rapid modeling of wireless communication channels</u> (PhD dissertation)	Douglas Horner, NPS	FY14
<u>An analysis of the defense acquisition strategy for unmanned systems</u>	Maj Courtney David Jones, USMC	FY14
<u>Terrain aided navigation for REMUS autonomous underwater vehicle</u>	ENS Jacob T. Juriga, USN	FY14
<u>Investigation of acoustic vector sensor data processing in the presence of highly variable bathymetry</u>	LT Timothy D. Kubisak, USN	FY14
<u>U.S. Army Unmanned Aircraft Systems (UAS)â€™s a historical perspective to identifying and understanding stakeholder relationships</u>	Donald R. Lowe, DON (Civ); Holly B. Story, DOA (Civ); Matthew B. Parsons, DOA (Civ)	FY14
<u>Preliminary design of an autonomous underwater vehicle using multi-objective optimization</u>	LCDR Sotirios Margonis, Hellenic Navy	FY14
<u>Da Vinci's children take flight: unmanned aircraft systems in the homeland</u>	Jeanie Moore, FEMA Office of External Affairs	FY14
<u>A comparison of tactical leader decision making between automated and live counterparts in a virtual environment</u>	MAJ Scott A. Patton, USA	FY14
<i>High Energy Laser Employment in Self Defense Tactics on Naval Platforms [RESTRICTED]</i>	LT Brett Robblee, USN	FY14
<u>Optimal deployment of unmanned aerial vehicles for border surveillance</u>	First LT Volkan Sözen, Turkish Army	FY14
<u>Domestic aerial surveillance and homeland security: should Americans fear the eye in the sky?</u>	LCDR Barclay W. Stamey, USN	FY14
<u>Lightening the load of a USMC Rifle Platoon through robotics integration</u>	LT Sian E. Stimpert, USN	FY14
<u>Small Tactical Unmanned Aerial System (STUAS)</u>	Christopher Ironhill, Bryan	FY13

<u>Rapid Integration and fielding process (RAIN)</u>	Otis, Frederick Lancaster, Angel Perez, Diana Ly, and Nam Tran	(SEP)
<u>Development and validation of a controlled virtual environment for guidance, navigation and control of quadrotor UAV</u>	Junwei Choon, Singapore Technologies Aerospace	FY13 (SEP)
<u>An examination of the collateral psychological and political damage of drone warfare in the FATA region of Pakistan</u>	Judson J. Dengler, U.S. Secret Service	FY13 (SEP)
<u>Integrating Unmanned Aerial Vehicles into surveillance systems in complex maritime environments</u>	LCDR Georgios Dimitriou, Hellenic Navy	FY13 (SEP)
<u>Improving the Army's joint platform allocation tool (JPAT)</u>	LT John P. Harrop, USN	FY13 (SEP)
<u>Active shooters: is law enforcement ready for a Mumbai style attack?</u>	Captain Joel M. Justice, Los Angeles Police Department	FY13 (SEP)
<u>The rise of robots and the implications for military organizations</u>	Captain Zhifeng Lim, Singapore Armed Forces	FY13 (SEP)
<u>Dynamic bandwidth provisioning using Markov chain based on RSVP</u>	Lieutenant Junior Grade Yavuz Sagir, Turkish Navy	FY13 (SEP)
<u>Systems engineering and project management for product development: optimizing their working interfaces</u>	Mariela I. Santiago, NUWC Newport	FY13 (SEP)
<u>Dynamic towed array models and state estimation for underwater target tracking</u>	LCDR Zachariah H. Stiles, USN	FY13 (SEP)
<u>Diver relative UUV navigation for joint human-robot operations</u>	LT Andrew T. Streenan, USN	FY13 (SEP)
<u>Closing the gap between research and field applications for multi-UAV cooperative missions</u>	Harn Chin Teo, ST Aerospace Ltd.	FY13 (SEP)
<u>Enhancing entity level knowledge representation and environmental sensing in COMBATXXI using unmanned aircraft systems</u>	MAJ James C. Teters,II, USA	FY13 (SEP)
<u>Real-time dynamic model learning and adaptation for underwater vehicles</u>	LT Joshua D. Weiss, USN	FY13 (SEP)

To aid new NPS students in their search for viable thesis topics, CRUSER maintains an iterative listing of potential thesis topics related to unmanned systems.

5. Student and Faculty Travel

CRUSER supported a several NPS student trips in FY14 to further their thesis work (*see Table 4*). NPS students were then required to give a trip report at a monthly NPS CRUSER meeting to further socialize their work.

Table 4. CRUSER funded student travel, FY14

Date	Student	Description
13-15 Nov 2013	Monica Farah-Stapleton	PhD Conference Presentation
6 Dec 2013	Isaac Donaldson Van Stuart	one day trip to vessel boarding networking and casualty support trial
8-13 Dec 2013	Stephen Williams	Student on the NPS UAs IFC project, meetings at NPS
27 Feb - 2 Mar	Maj Bill Mamourieh	Site visit to Denver
13-15 Mar	LT Steven Terjesen	NAVAIR Site Visit
14 Mar 2014	LT Nahum Camacho	Observe Mfg of Solar Glider
3-13 May 2014	LT Adam Sinsel	WMD-ISR Experimentation in Poland
3-13 May 2014	Capt Robert Schulz	WMD-ISR Experimentation in Poland
6-9 May 2014	LT Nahum Camacho	JIFX Experimentation
May 2014	LT Brad Penley	
16-22 Jul 2014	LT Nick Valladerez	Key Largo experimentation
20 - 25 Jul 2014	LT Matthew Mitchelson	NASA NEEMO event in Key Largo, FL.
23-30 Jul 2014	LT Chase Dillard	Key Largo experimentation
4-9 Aug 2014	Capt Thomas Rice, USMC Maj Tom Chhabra Maj Erik Klein	MC Warfighting Lab
10-13 Aug 2014	Capt Caroline Scudder	JIFX
10-15 Aug 2014	LT Daniel Lee LTJG Ercan Aras Capt Robert Schulz	Alameda Experiment

13-14 Aug 2014	GySgt Joffre Castillo	Cyber Operational Architecture Training System (COATS) demonstration
23-24 Sept 2014	Eric Williams	Monterey SE Capstone Presentation
29 Sept - 3 Oct	Capt Caroline Scudder	Site visit to MAWTS-1

B. RESEARCH AND EXPERIMENTATION

At the direction of the SECNAV, NPS continues to leverage long-standing experience and expertise in the research and education of robotics and Unmanned systems to support the Navy's mission. CRUSER was established to serve as a vehicle by which to align currently disparate research efforts across the NPS campus as well as among our academic partners and greater community of interest. Funding in FY14 was granted to twenty NPS faculty members to research many diverse aspects of unmanned systems including increasing education opportunities in addition to research.

In September 2013, CRUSER made its second call for proposals to seed research topics. The stated funding period was 31 October 2013 through December 2014, and the funding levels were set at \$75,000 to \$125,000 per proposal. Like in FY13, researchers were again asked to submit proposals in one of the following general subject areas:

- **Technical:** Power, Sensors, Controls, Communications, Architectures, Human Factors, Information Processing and Dissemination
- **Organization and Employment:** Human Capital Requirements, Risk Analysis, Force Transition, Acquisition, Policy, Concept Generation evaluation and Authorities
- **Social, Cultural, Political, Ethical and Legal**
- **Experimentation**
- **Defense against threat unmanned capabilities**

Due at the beginning of September 2013, over 20 proposals totaling over \$3 million in requests were considered for CRUSER funding. The CRUSER advisory committee selected nearly sixteen projects, and granted \$1.5 million in total to support their work in FY14 (*see Table 5*). Additional support has been provided to four more projects totaling \$700 thousand.

Table 5. FY14 CRUSER funded projects (alphabetized by Principal Investigator last name)

PRINCIPAL INVESTIGATOR(S)	PROJECT TITLE
Bordetsky	Diver and Unmanned Vehicle Networking-by-Touch

Chu	UUV Path Planning for ASW/MIW Using Navy's Ocean Data
Chung	Innovating for the Swarm vs. Swarm Grand Challenge Competition
Davis, Brutzman	A Robot Control Ontology Supporting Ethical Mission Execution
Du Toit, Horner	Joint Human/Robot Operations in Extreme Environments
Du Toit, Horner	Robotic Outposts to Support Persistent AUV Operations
Guest, P.	Development of Very-Small Multi Rotor Aircraft as Platforms for Atmospheric and Sea Surface Measurement
Harkins, Vaidyanathan	A Teleoperative Sensory-Motor Control Platform (TSMCP)
Harr	Tropical Cyclone Reconnaissance with the Global Hawk: Assessment of Initial Results and Use in Improving Forecasts of Tropical Cyclone Intensity and Structure
Jenn	Short Range Radiative Wireless Power Transfer (WPT) for UAV/UAS Battery Charging
Jones, Dobrokhodov, Kaminer	Aqua Quad
Joseph, J	Glider applications in Tactical Oceanography
Kaminer, Jones, Dobrokhodov	Defense against Swarms: A Key Naval Capability
Millar	UAS IFC Phase II: BBN Based Hazard Risk Analysis Toolset
Nissen	Command & Control of Highly Autonomous Systems and People
Smith, Horner	Real-time undersea networking using acoustic communications for improved AUV positioning and collaboration
Wang, Smith, K	Environmental Data Collection Using Autonomous Wave Gliders

Some of these projects are complete, others are underway, and a few have yet to begin work as the period of performance ends on 31 December 2014. These research summaries are listed in alphabetical order by primary Principal Investigator (PI) last name, and each has a POC listed for further inquiry.

1. Diver and Unmanned Vehicle Networking-by-Touch

The study unfolded through a series of major field experiments conducted in May, June, and August of 2014 and different partial trials and development steps made during the course of FY14:

Part A

Part A of the series was conducted during the MIO WMD-ISR experiment with NPS students and NATO SOF units in Poland from May 6-13, 2014. By integrating Unmanned Vehicle networking into the vessel boarding and coastal area search Direct Action (DA) and Site Exploitation (SE) activities, we determined that:

- Network-controlled miniature UGVs that drop off unattended relays appear to have potential in enabling WMD-ISR integration into the high tempo DA-SE sequence.
- There are encouraging results from dropping-off unattended sensor simulators (short haul tag readers) during both “low visibility” area search and networked SE. They show a possible path to integrate WMD-ISR via multiple simple detection events that are individually uncharacteristic, but together bring key adjudication information.
- Such a process could intertwine with ad-hoc dispersion of relays, and facilitate uninterrupted networking, and reinforce data fusion for remote technical Subject Matter Experts (SMEs).

The experiment provided answers to the major research question: *How does integration of a micro UAV with a small UGV improve low visibility stand-off detection?*

Findings:

The experiment yielded two successes.

- 1) Integration of a micro UAV operated by NORSOF during a DA/SE event at the Hel peninsula on northern Poland went well. Visual site exploitation, including facial screening by the micro UAV at the exploitation site in Hel, was transmitted successfully during the DA pre-screening of the area. A detailed description of the operation of the micro UAV will be provided in the full report.
- 2) The integration of three UGVs, one iRobot (NORSOF), and two stair-climbing, gripper enabled Micro Tactical Ground Robots (MTGR) from the Israeli Roboteam created a new technology support solution. These tools enable the integration of WMD-ISR information during high tempo DA/SE sequences. Beginning with Phase I at the Gdansk Technical University and Phase II at the Hel peninsula site Low Visibility search (preceding the DA), the UGVs enhanced both the ISR data collection and the DA on-the-move surveillance. One MTGR conducted low visibility video surveillance and transmitted it back through the network, while the other MTGR transmitted video feeds of the outside areas to the FOB, by accompanying the DA team from the assault boats to the target building. The MTGR’s visibility was so low that the DA team didn’t notice it during their entry of the building, search, and eventual live firefight. As a result, the FOB had a clear video presence and SA of the DA site.

During the large ship vessel search (*see Figure 9*), the MTGR transported a small rad/nuc detector and a LLNL adaptive monitor, offering a good proof of concept that it could be used effectively for stand-off detection in close quarters.

The UGVs emplaced relays during the Low Visibility search and SE that followed the DA with only minutes of delay. Such robust UGVs may offer a major unmanned technology component to enable ubiquitous networking and low visibility stand-off detection for integrated WMD-ISR operations.



Figure 9. The Micro Tactical Ground Robot (MTGR) is piloted along the hull of the Copernicus target vessel in search for a radioactive substance.



Figure 10. Establishing the Boarding Team mesh network to link

The Boarding team set up a mobile network (*see Figure 10*), which reached back to the FOB, JCBRND CoE in the Czech Republic, and back to the NPS NOC in Monterey, California. Once established, the Boarding Team successfully stretched the network. They then brought POLSOF members aboard the vessel and familiarized them with the network and allowed them to operate the robotic systems from Roboteam.

Problems encountered:

Unfortunately, bad weather cancellation of helicopter transport to the oil rig prevented the POLSOF and the source handling team from conducting events at both the Radzikowo airfield and subsequently aboard the oil rig. Accelerated departure of troops to the distant oil rig prevented us from practicing Boarding Team-to-Cutter/MOC-to-Reachback SME communications. This would have enabled us to collect vessel boarding WMD-ISR operation performance data. However, this task was conducted during our set of trials at NMIOTC in Souda Bay, during June, 2014.

Part B

Part B of the study was held during the MIO WMD-ISR experiment with US and NATO Maritime Interdiction crews at NMIOTC in Souda Bay from May 6-13, 2014

It focused on innovative UAV-Diver networking and a new type of relaying technique in the austere environment of a large vessel.

Findings:

The experiment demonstrated success in applying networking by near field touch to communicate between UAV operators who were augmenting the vessel/area search (see *Figure 11*), with combat subsurface divers supporting the action.



Figure 11. Networked UAV in the starting position before providing aerial images to divers



about 5 feet behind the end of the helo deck - Moving away from helo deck, stbd side, no detection, lost imagery - Helo moving away too far from the material - instruct to move closer - Instruct operator to perform a passover to see if there's a detection - End mission at 1050 local time - One good reading - 1052 Detection visual right before the UAV landed			
6/13/2014 08:45:23	BO RSE: As per instruction, I am submitting data captured during UAV observation for material detection.		✗
6/13/2014 05:50:21	NPS MOC: Commencing Friday operations		✗
6/12/2014 19:59:11	CWIX MOC2: Request uploading XML track data file from CoT to execute CWIX tests.		✗
6/12/2014 13:43:28	MOC CORE: RapterX- Tracking Sensor with Cursor on Target.	 Replace Delete	✗
6/12/2014 13:37:31	MOC CORE: Ship map from ATak added to Raptor X allowing for a more defined view of the target space.	 Replace Delete	✗
6/12/2014 10:51:07	Dive Node: Diver received picture from helo	 Replace Delete	✗

Figure 12. Divers on the way to objective and the associated experiment log.

The experiment log in Figure 12 indicates successful transmission to divers of images of coastal area approaches taken by the UAV (see Figure 13).

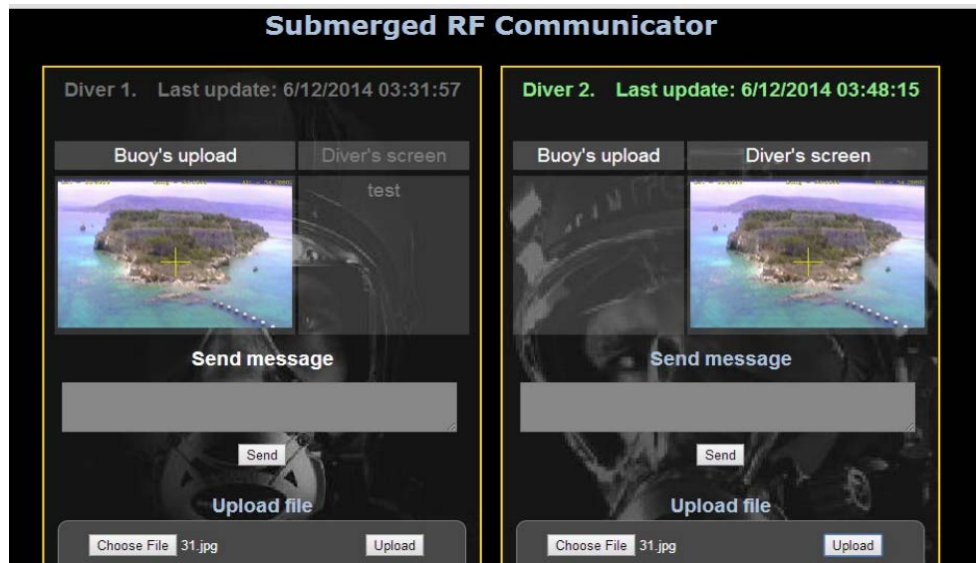


Figure 13. UAV taken images transfer to submerged divers.

Problems encountered:

The dialog in Figure 14 illustrates that although the UAV-Diver networking process worked well, a few technical problems were encountered, but the overall task was accomplished with success.

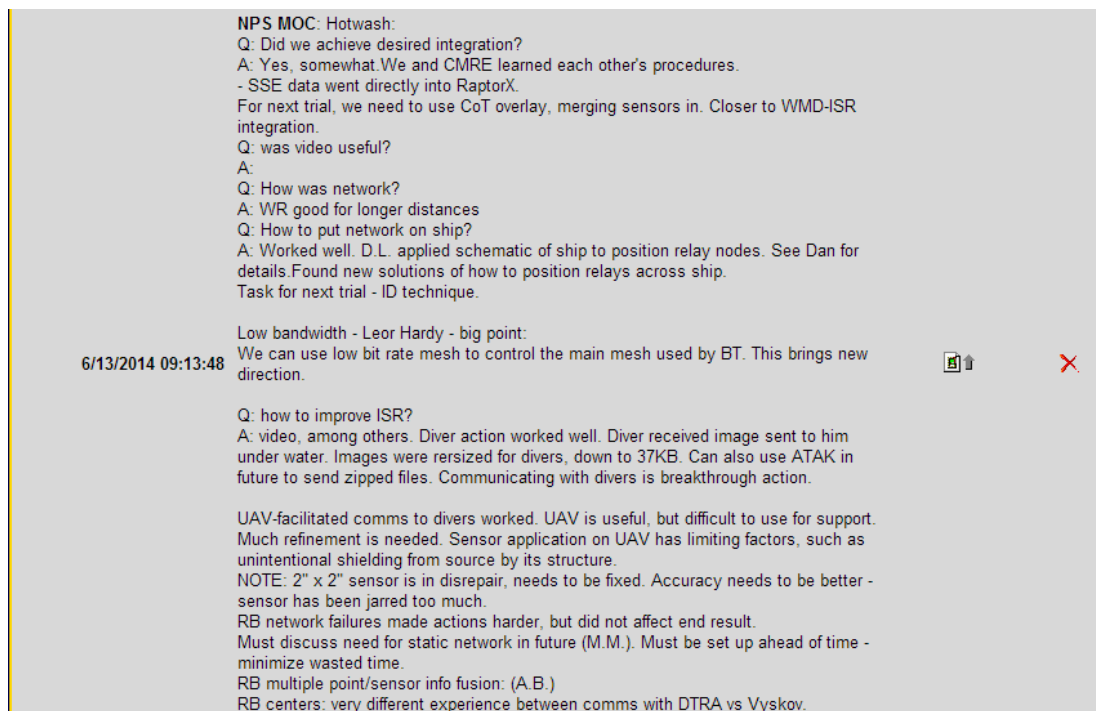


Figure 14. Problems encountered discussion snapshot

Part C

Part C of the study was done during the MIO-JIFX experiment with USCG and SFPD Marine Police Boarding and Patrol units in SF Bay on Aug 11-15, 2014. This experiment allowed us to address an important task of USV/AUV-Diver networking.

Findings:

The USV/AUV was modeled by the USCG remotely operated vehicle (ROV) team. The experiment demonstrated successful exchange of ship search images captured by the USCG ROV (see Figure 15) and submerged diver conducting the stern area search for a parasite box. It was cut short due to the diver's health condition.

Additionally, the experiment allowed refining the UGV-relay networking during the vessel boarding action.

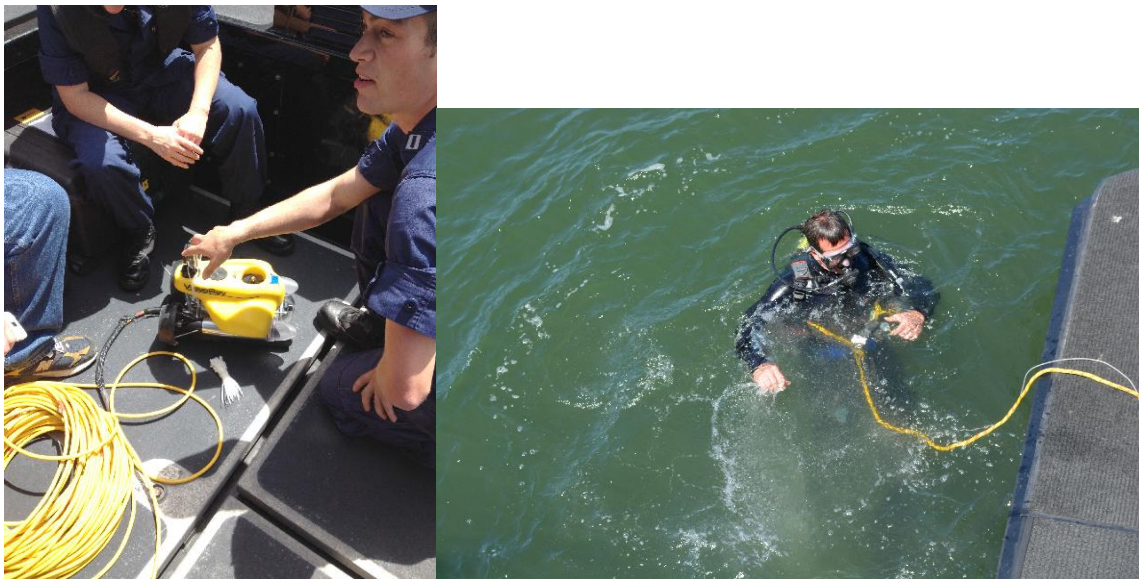


Figure 15. ROV-Diver networking

Conclusion:

Altogether, the series of three field experiments allowed us to explore and demonstrate the solutions for UGV augmented vessel boarding networking, UAV-Diver networking, and USV/AUV-Diver networking options. Our next step in this direction will be to conduct UGV-Diver networking during a large vessel boarding, then integration of all tested assets into a seamless cooperative Boarding Team-UAS-Diver network.

POC: Dr. Alex Bordetsky (abordets@nps.edu)

2. UUV Path Planning for ASW/MIW Using Navy's Ocean Data

The longterm goal of this project is enhancement of unmanned undersea vehicle (UUV) 's capability for ASW and MIW such as accurate localizing, detecting, classifying, and tracking targets in real-time.

Objectives

Highly efficient methodology and algorithm will be developed to optimal UUV path planning and to analyze ASW/MIW related ocean environment from sea gliders. In collaboration with the Naval Oceanographic Office (NAVO), the Navy's ocean data such as the bathymetry, bottom roughness, ocean velocity, temperature, and salinity will be implemented into the UUV path planning with long endurance. It will contribute to the establishment of a mission-focused UxS platform in concert with mission module development plans.

Problem

UUV would greatly benefit ASW and MIW. However, difficulty in predicting its underwater trajectory may limit its applications. For example, to conduct ASW/MIW effectively, accurate localization of UUV is important because observed ocean data or the enemy target information can be more useful when the location of the UUV is precise. Taking glider as an example, the glider's velocity is compared to that of other UUVs due to their buoyancy-driven propulsion system. Typically, the horizontal velocity is about 0.4 m/s, which is the same order of magnitude as the ocean currents. Thus, the glider's movement is strongly affected by the ocean currents. In addition, gliders do not have sensors for measuring their position and the subsurface ocean currents in real time, and they can only receive a Global Positioning System (GPS) fixed position when they are located at sea surface. Consequently, given that some margin of error is common between the dead reckoning (DR) position and the real surfacing position (see P_{gps} in Figure 16), knowing their actual underwater location is difficult. Effective utilization of the surfacing position P_{gps} to determining the underwater trajectory is important and challenging.

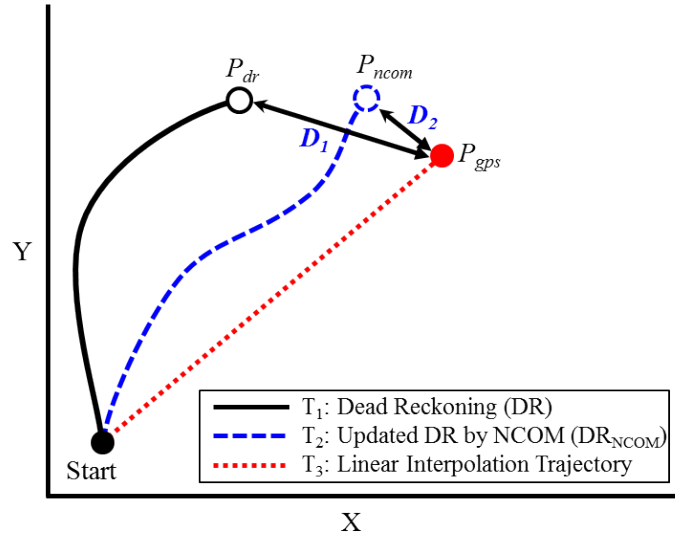


Figure 16. Errors in estimating underwater glider's trajectory.

Approach

The project is divided in two major parts: (1) optimal determination of UUV trajectory using NCOM, and (2) UUV path planning on the base of the results from the first part. The underwater Slocum glider is chosen for this study as a UUV. The Slocum glider data and the Navy 's Coastal Ocean Model (NCOM) output are used for the development of an optimal determination of UUV 's underwater trajectory with depth-dependent correction.

A field experiment was conducted in the course entitled "OC4270 Tactical Oceanography" offered by the Oceanography Department in the Monterey Bay (see Figure 17) from January 30, 2014, to February 1, 2014, with 68 dives.

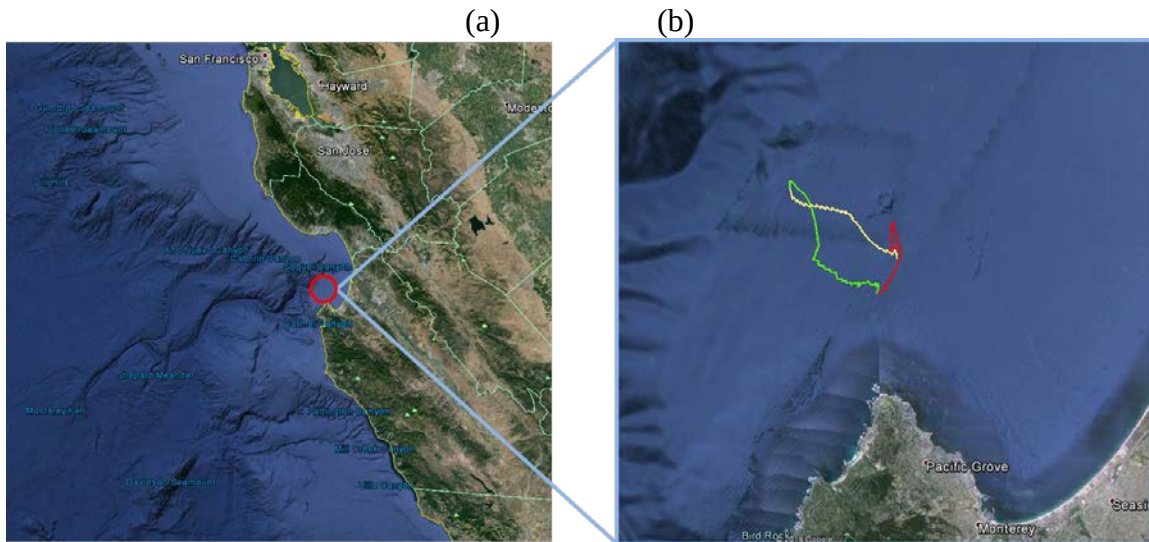


Figure 17. Field experiment conducted in the Monterey Bay from January 30, 2014, to February 1, 2014, with 68 dives: (a) experiment area, and (b) trajectories of the Slocum glider.

During the three days of deployment time, the Slocum performed 68 dives. The average straight distance of DR trajectory is about 362 meters, with a minimum of 112 meters and maximum of 623 meters, depending on the prescribed depth and location. The average time of a single dive was about 20.5 minutes, and the average time of staying at surface was about 10 to 15 minutes. In addition, the average of maximum depth was about 95 meters, with maximum depth of about 198 meters. After finishing the three-day mission, the Slocum's basic navigation data were processed with MATLAB. The data included time; pressure; and the data for three main positions, i.e., GPS fixed position, DR position, and linear interpolation position.

The NCOM for Monterey Bay is used with a high resolution of 1/30 degree (Metzger et al. 2014). Its model output such as ocean velocity is updated at 00Z with the four-day (96 hours) forecast and three-hour increments.

This project is a multi-institutional effort between NPS, NUWC-Newport, and Naval Oceanographic Office.

- Peter C. Chu, Chenwu Fan, and LCDR JooEon Shim (Korean Navy), Vance Villarreal (USN) at NPS have been working on the methodology and algorithm development.
- David Cwalina at NSWC-Newport has been working on the application of UUV for ASW.
- Ronald Betsch and Pete Frischer at the Naval Oceanographic Office have provided ocean environmental data and guidance for UUV with application on ASW and MIW.

Results

An optimal scheme has been developed to determine the Slocum glider's underwater trajectory using the NCOM model. This algorithm shows great improvement of the positioning using the NCOM velocity output. It reduces the surfacing position error from D_1 around 168.9 m without NCOM (i.e., dead reckoning) to D_2 around 169 m 63 m with NCOM (see *Figure 18 and Table 6*). The top view of optimally determined underwater trajectory is shown by the black curve in *Figure 19*. Here, the dive #53 is used for the illustration.

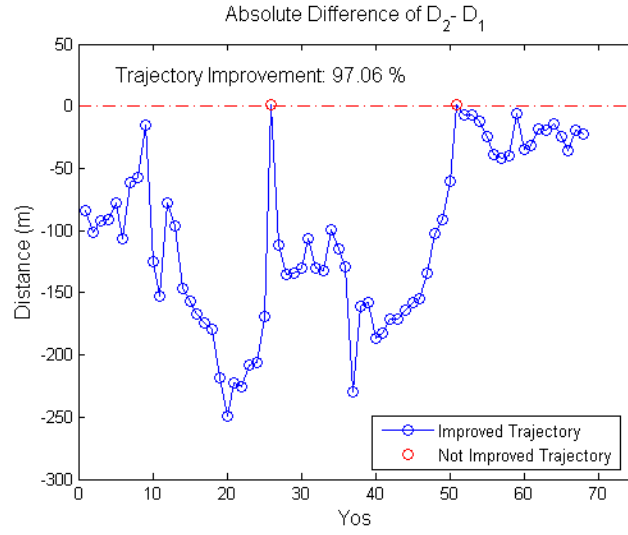


Figure 18. Error reduction ($D_2 - D_1$) for all the 68 dives of the Slocum glider.

Table 6. Error statistics for D_1 (without ocean model) and D_2 (with ocean model).

Distance	$D_1 (P_{gps} - P_{dr})$	$D_2 (P_{gps} - P_{ncom})$
Mean	168.895 m	62.970 m
Minimum	38.421 m	7.219 m
Maximum	295.417 m	264.922 m
Median	167.170 m	50.697 m
Standard Deviation	66.147 m	40.196 m

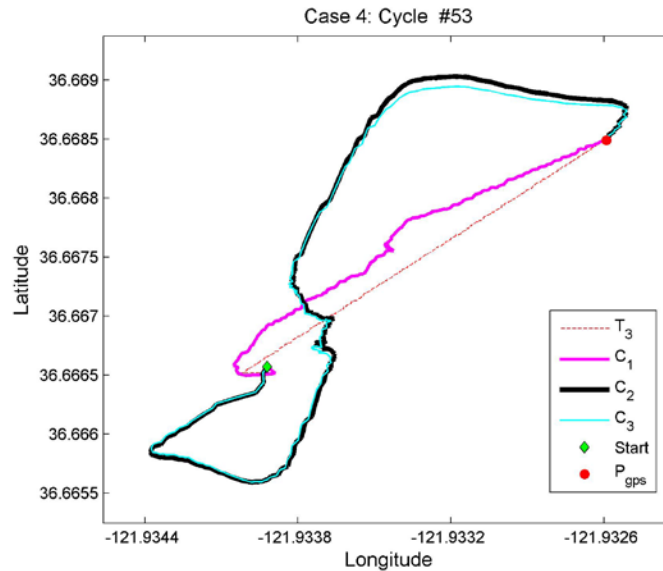


Figure 19. The top view of optimally determined (black curve) and dead reckoning determined underwater trajectories for the dive #53.

Work Completed

- (1) The first-type algorithm has been developed to incorporate the NCOM velocity output into the hydrodynamic model for reduction of position error.
- (2) The second-type algorithm has been developed to optimally determine UUV's underwater trajectory with the surfacing GPS position correction.
- (3) The third-type algorithm has been developed to obtain ASW related parameters such as the sonic layer depth, and ocean mixed layer depth from underwater glider data.
- (4) Two students are finishing their MS theses (Sept 2014, USW curriculum) in this project. Their theses greatly improve the positioning of underwater glider and the analysis of glider data for ASW application.

NPS MS Theses Completed

The results were published in two USW theses:

Shim, JooEon. *Optimal Estimation of Glider's Underwater Trajectory with Depth-dependent Correction using the Regional Navy Coastal Ocean Model with Application to ASW*. MS thesis in Physical Oceanography, Naval Postgraduate School, September 2014.

Villarreal, Vance. *Relationship between the sonic layer depth and mixed layer depth identified from underwater glider with application to ASW*. MS thesis in Physical Oceanography, Naval Postgraduate School, September 2014.

Impact and Applications

The new method can be used to any UUV 's underwater positioning, which will greatly impact on the advances in science and capability in Naval operations.

Related Projects

This project is related to the research project entitled "Littoral Oceanography for MIW/ASW with Underwater Unmanned Vehicle (UUV)" (PI: Peter Chu) funded by the Naval Oceanographic Office 's ASW/MIW Programs (Program Manager: Ronald Betsch). The results obtained from this project contributes to the related project.

POC: Dr. Peter Chu (pcchu@nps.edu)

3. Innovating for the Swarm vs. Swarm Grand Challenge Competition

This effort seeks to expand the scope of extensive ongoing student and faculty research in the area of the Swarm vs. Swarm UAV grand challenge competition, designed by the Advanced Robotic Systems Engineering Laboratory (ARSENL, arsenl.nps.edu) to inspire new concepts of operations and illuminate new tactics in unmanned systems employment, specifically in the swarm and counter-swarm robotics arenas. The competition scenario involves a tournament of live-fly, large scale "battles," where in each such battle two teams comprising many autonomous aerial robots vie for air superiority while simultaneously defending a high value unit on the ground and/or attacking that of the opponent's. Active ongoing research in the ARSENL on the project represents an integrated concept generation, modeling, simulation, and field experimentation effort to design, develop, and deploy a swarm versus swarm UAV live-fly engagement experiment.

This ongoing research explores opportunities to significantly leverage open source technologies, e.g., vibrant open source software communities for robot operating systems and active development for open hardware designs for UAV autopilots, as well as commercial- and government-off-the shelf (COTS and GOTS) products. Additional aligned topics include research thrusts in mission-level autonomy, human-robot interactions, bio-inspired tactics (such as swarming and active herding), test and evaluation methodologies for unmanned systems, and even policy implications for employment of swarming unmanned systems in modern warfare.

In FY14, ARSENL has conducted eight live-fly field experimentation events, representing the aggressive pace of development necessary to advance the state-of-the-art in this rapidly evolving field.

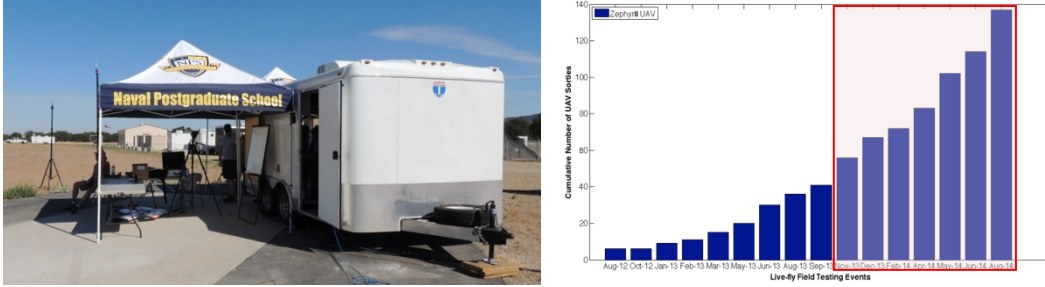


Figure 20: NPS ARSENL field experimentation trailer and ground control station setup (left) and histogram of cumulative sortie counts, with those sorties conducted in FY14 sorties highlighted and showing accelerated development (right)

Advancing Technologies

Flight Systems using Open-Source and Commodity Components: A key initiative for FY14 was the design, iteration, fabrication, and finalization of our flight systems. This effort included a streamlined production capability as well as integration of low-cost, commodity hardware and open-source technologies (e.g., the Pixhawk autopilot).

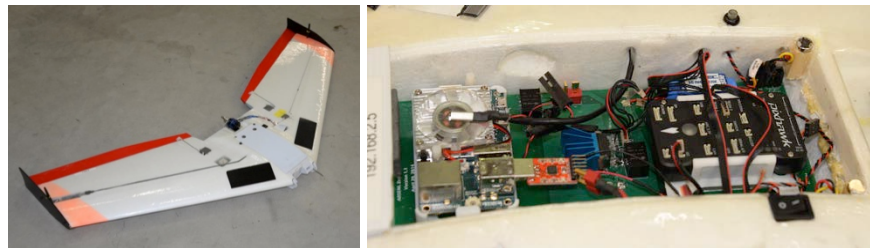


Figure 21: Customized ZephyrII UAV, Generation E, representing finalized flight systems integration and design (left) and integrated avionics and autonomy payload (right)

Swarm Autonomy Development: The enhancements and stabilized design of the flight platforms, ARSENL has been able to accelerate its focus towards one of its key interest and expertise areas, i.e., swarm or collaborative autonomy. A major development includes the use of Robot Operating System (ROS) as the open-source autonomy architecture onboard the aircraft, which is used to perform autonomous capabilities, interface with the autopilot, and handle interactions with teammates.

Swarm Networking and Communications: Based on previous experiences with multi-UAV operations, the communication network also highlights a present challenge for swarm flight operations. ARSENL has identified and implemented a network architecture that is anticipated to enable scalable communications, leveraging open-source software for mesh network capabilities (i.e., B.A.T.M.A.N.-adv). This architecture has enabled coordinated flight using these wireless links, such as multi-UAV “follow-me” flight tests.

Support and Outreach

NPS Students: ARSENL has supported numerous theses and project courses throughout FY14, including five student thesis efforts in Systems Engineering, Computer Science, MOVES, and

Operations Research. Additionally, ARSENL supported aligned course projects, such as SE4900, which involved three students developing multi-quadrotor algorithms for potential use with swarm systems, and SE320x, which leveraged a team of seven Systems Engineering students to design, build, and test a multi-UAV launcher.



Figure 22: A team of Systems Engineering students design and build a multi-UAV launcher, based on end-user needs and system requirements (*left*) and conduct tests of their prototype design (*right*)

ARSENL Interns: ARSENL hosted nine interns in FY14, including one USMA and one USAFA cadets, as well as three high school students, two undergraduate students, and two graduate students through the ONR-managed Science and Engineering Apprenticeship Program (SEAP) and the Naval Research Enterprise Internship Program (NREIP). Projects ranged from development of pursuit-evasion algorithms for ground robots (that could translate to aerial combat) to implementation of a software continuous integration server to streamline verification and validation of flight software developments.

Reservists: ARSENL continues to work closely with the ONR/NRL S&T 113 USN Reserve Unit, with unit members assisting with field experimentation activities, operational knowledge exchange, and flight platform fabrication and flight tech training efforts. Their frequent and regular involvement have greatly enhanced and contributed to this ARSENL effort, with significant ongoing and future interactions planned in FY15.



Figure 23: A USNR unit member performs a UAV launch (*left*) and another USNR unit member assists with pre-flight checks (*right*)

POC: Dr. Timothy H. Chung (thchung@nps.edu)

4. A Robot Control Ontology Supporting Ethical Mission Execution

This research is still ongoing, and a research summary was not available at the time this report was released. Per the research proposal, this work will define requirements and possible components of a robot command and control ontology supporting practical realization of ethical autonomous vehicle operations. This will compliment and extend previous work with the Rational Behavior Model (RBM) tri-level hybrid robot control architecture.

Ethical operation of unmanned systems is becoming a topic of significant importance not only for operators, but for decision-makers, developers, and ethicists as well. At the same time, increasing onboard computational capabilities have enabled these systems to operate with more autonomy and to conduct increasingly complex missions with little or no human intervention. A number of approaches to the implementation of ethics for unmanned have been suggested. Many of these are premised on the availability of robust AI algorithms

Current research work at NPS has demonstrated practical approaches for ethical reasoning to govern robot behaviors. These consist of applying ethical constraints to existing patterns of robot planning in a manner that matches real-world operational constraints, rather than creating some new paradigm for philosophical contemplation. This approach is intentionally patterned after similar patterns used by military forces, which often must operate in a loosely coordinated fashion while observing highly consistent rules of engagement (ROEs). Our focus is on maritime robotics supporting fleet and coalition naval forces. The same ethical patterns also appear to be applicable to scientific and commercial use of unmanned underwater systems.

This proposed work leverages previous NPS work in autonomous execution of robot missions relying on the Rational Behavior Model (RBM), a tri-level hybrid control architecture that effectively links high-level symbolic processing associated with mission planning and control to largely numerical computation required for real-time vehicle control and sensor processing. In the vocabulary of the RBM formalism, the Execution Level is the lowest layer of vehicle control software and is concerned with carrying out the hard real-time tasks typically associated with physical interaction of a vehicle with its surrounding medium. The middle RBM layer, the Tactical Level, is organized as a set of behaviors that can be controlled and executed through Execution Level functionality. These behaviors include not only routine behaviors such as maintaining course and depth, sonar obstacle avoidance, etc., but also more complicated behaviors such as mapping, waypoint navigation, search planning, and response to emergency situations. The highest level of software in the RBM architecture is called the Strategic Level, which to the commanding officer of a manned vehicle. Unlike the Tactical and Execution Levels, the Strategic Level conducts only symbolic computation in a time-independent, non-numeric mode. The Strategic Level operates entirely in the domain of mathematical logic to determine which high-level mission goals to pursue based solely on the success or failure of the previous high-level goals. Thus, Strategic Level reasoning is conducted without regard for vehicle state and is based solely on the Tactical Level's understanding of when the currently executing goal is successfully achieved, has failed to be achieved, or can no longer be pursued without violating ethical constraints.

Recent work has resulted in a rigorous mathematical model for the RBM Strategic Level controller. This model formally defines RBM semantics in mathematical terms as a generalization of a Turing Machine (TM) into a broader class of automata, Mission Execution Automata (MEA). The crux of TM generalization to MEAs is allowing the external agent to be not only a tape recorder, but alternatively, either a human being or the Tactical Level of a sensor-based robot. An MEA includes a finite state machine (FSM) definition of a robot mission where states represent individual goals to be achieved and transitions are executed upon goal success or failure.

For UUVs operating in high-risk environments, it is our contention that it is a moral imperative that human operators be legally accountable. The mathematical formalism provided by MEAs directly supports this level of accountability because its determinism allows mission orders to be subjected to exhaustive testing before actual robot execution. When such testing has been completed, the senior mission specialist can formally approve orders as an executable specification for the subsequent generation of robot mission orders by robot specialists. The mission specialist then can reasonably assume legal accountability for any errors in mission orders. Further, mission orders specified in an executable form such as appropriately structured Prolog or XML can be read declaratively by non-programmers (e.g., mission specialists) to provide the kind of transparency needed for after action review and possible legal proceedings relating to loss of life or property.

Much previous work in this project has been dedicated to establishing a common declarative language, the Autonomous Vehicle Command Language (AVCL) for expressing parameterized Strategic Level goals and simple Tactical Level behaviors. In addition, complex Tactical Level behaviors have been developed for state-based accomplishment of Strategic Level goals. To date, 13 Strategic Level goal types have been defined along with corresponding complex Tactical Level behaviors. In addition, the proposed application of RBM to ethical autonomous robot missions will require the definition of ethical constraints that can be assessed by the Tactical Level. Specifically, in the course of attempting to satisfactorily complete a Strategic Level goal, the Tactical Level continuously assesses the status of Boolean constraints that, if violated, will constitute a goal failure for ethical reasons.

Successful experiments both in simulation and actual vehicles have been encouraging, but potential limits to the current approach are beginning to become apparent. Ultimately, any attempt to exhaustively list available goal types for Strategic Level execution and constraint types for Tactical Level evaluation will eventually limit the complexity of the missions expressible with AVCL or executable by the MEA. From a practical standpoint, a Strategic Level goal can be described as any activity that can be realized through the execution of simple or complex Tactical Level behaviors (i.e., if the Strategic Level directs the Tactical Level to execute a goal, the Tactical Level can do so). Similarly, a constraint can be described as any Boolean condition that can be assessed by the Tactical Level (i.e., the Tactical Level can continuously determine the value of all valid constraints). A more scalable approach, therefore, might be to provide a framework in which arbitrary goals and constraints can be defined for use in one or more vehicles.

Description Logics (DL) are a family of logic-based knowledge representation systems with semantic expressiveness falling between Propositional Logic and First Order Logic (FOL). That is, they are more expressive than Propositional Logic, but less so than FOL. In addition to significant semantic expressiveness, algorithms exist to automatically reason with ontologies described with DLs. Because of these characteristics, DLs are heavily relied upon for Semantic Web technologies with the *SROIQ* DL providing the basis for the primary language for defining Semantic Web ontologies: the Web Ontology Language (OWL). Many of the characteristics that make DLs attractive for Semantic Web applications can also be leveraged in developing a framework for describing autonomous vehicle missions to be tested and executed by an MEA running in simulation or a real vehicle, or relying on a human critic.

This work will include an analysis of requirements for specifying arbitrary autonomous vehicle goals and constraints as described previously. This analysis will focus on autonomous underwater vehicle (AUV) operations. It is believed that results will be generalizable to other classes of vehicle. In addition, this work will utilize open source and other commercially available tools to develop an exemplar ontology for AUV command and control using OWL 2.0. This exemplar will include backward compatibility with the existing AVCL vocabulary. Finally, open-source tools will be utilized to incorporate functionality into the NPS AUV Workbench for working with missions described with the exemplar ontology. Baseline AUV missions will be developed and included in the AUV Workbench distribution. These baseline missions will assure repeatability of any published test results and will provide examples from which further missions can be developed. This work will be incorporated into larger NPS research projects that include testing in both vehicles and simulation.

POCs: Dr. Duane Davis (dtdavi1@nps.edu) and Dr. Don Brutzman (Brutzman@nps.edu)

5. Joint Human/Robot Operations in Extreme Environments

The research objective is to develop autonomous navigation techniques to survey and conduct operations in difficult or extreme environments. Conceptually this is accomplished with a complimentary tandem of unmanned systems. A first vehicle provides an initial assessment of the area by conducting a rapid survey. The second vehicle uses a feature-based navigational map built from the sensor data of the first mission for two types of objectives – a more detailed survey and a joint human-robot mission. This approach requires advances in navigation that focuses on spatial sensor systems input into a control feedback loop to ensure safe and effective operations.

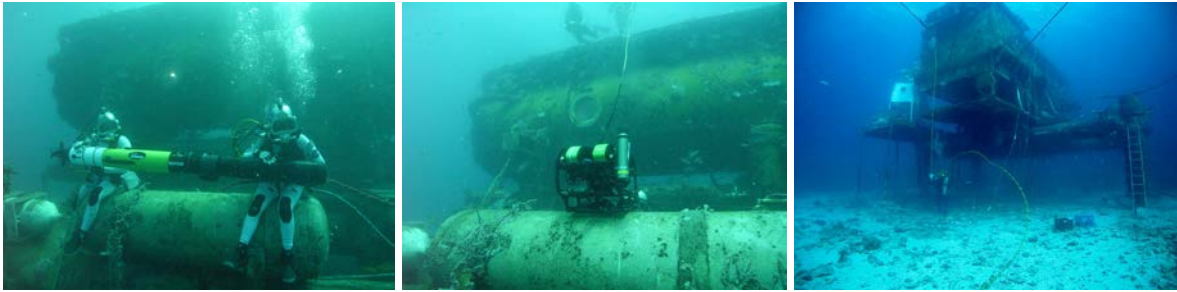


Figure 24: NPS CAVR REMUS 100 with Astronauts (top left) and the Tethered, Hovering Autonomous Underwater System, THAUS, (bottom center) at the Aquarius Habitat (top right)

This project built on a prior collaboration between NPS Center for Autonomous Vehicle Research (CAVR) and NASA Johnson Space Center (JSC). The collaboration evaluated the effects of autonomy on mission effectiveness for joint robot-human operations during NEEMO (NASA Extreme Environments Mission Operations). For a wide variety of DoD operations, teams are tasked with conducting operations in potentially dangerous environments. Examples include shipboard searches, Close Quarter Combat (CQC), Search and Rescue and Mine countermeasures. Unmanned systems can dramatically improve safety and situational awareness prior to, and in tandem with personnel conducting these missions. Technologies necessary to facilitate human operations in the undersea extreme environment (including joint human-robot exploration) are developed and evaluated. The two-phase mission profile highlights the technological challenges:

Phase One – Initial Rapid Survey: When operating in an unknown environment, it is frequently useful to have a rapid assessment for subsequent planning. Time is the key. It will determine the survey resolution that is possible. For an undersea mission, a single prop, torpedo-shaped AUV with a complimentary sonar sensor suite (side-scan, forward looking and downward looking sonar) is an energy efficient, rapid assessment tool. CAVR utilized the REMUS 100 AUV. The information collected includes high-resolution bathymetry and currents. Localization accuracy critically affects the quality of the survey map. In this work, Feature Based Navigation (AUV localization using detection of points features from a forward-looking sonar) was combined with Terrain-Aided Navigation (AUV localization using the bathymetry data from a downward looking sonar). A particle filters approach for vehicle navigation, which combined a smoothing filter with the particle filter approach into a single stochastic framework, was implemented. The combination of the approaches holds the promise of improving the robustness and accuracy in environments where GPS is not available. This work on Terrain-Aided Navigation was partially performed by ENS Jake Juriga as part of his thesis research.

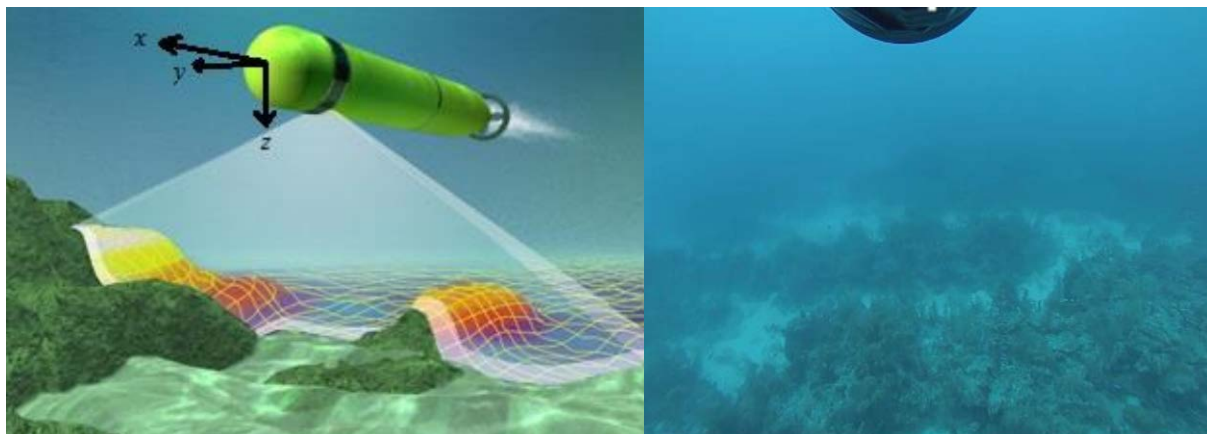


Figure 25. Terrain-Aided Navigation concept (left) and view from REMUS 100 at Aquarius (right).

Phase Two – Joint Human-Robot Missions: Using the “course” map developed by the initial survey, regions are selected for detailed study. For example, the bathymetry map created by the AUV is a “2 ½ dimensional” or a fly-over representation of the terrain. The detailed site survey uses this information for navigation and to build a true 3-dimensional representation of the environment and to perform tasks in collaboration with human divers. The following capabilities were investigated: (i) Vectoring/Site navigation – For cluttered and limited visibility environments, site navigation can be critically challenging and effects operational safety and mission effectiveness. THAUS’ vectoring capability quickly leads a diver to an objective, wasting little dive time (and air) on finding the site. This task was partially executed by LTJG Jose Alberti as part of his thesis research on Behavior-based control algorithms for robust vehicle control in diverse operational scenarios. (ii) Sensor assisted tele-operation of the THAUS platform allows remote operators (i.e., on the surface or in the Aquarius habitat to explore potential work sites in detail. (iii) Robotic Assistive capabilities investigated included tool delivery, asset recovery, and situational awareness for the mission commander. This task was partially executed by LT Nick Valladarez as part of his thesis research on Adaptive Control-based vehicle stabilization for complex, interactive diver-robot mission execution. (iv) High resolution mapping and data gathering was investigated using forward and micro-bathymetry sonars by LT Matt Mitchelson as part of his research into 3D environmental sensing and representation to enable close-quarters AUV operations.

Outcomes: NPS CAVR participated in the NEEMO 18 mission, in collaboration with NASA Johnson Space Center in July 2014. During this mission, CAVR deployed the REMUS 100 AUV for *phase 1* operations, and THAUS AUV for *phase 2* operations.

For phase 1, more than 1 million measurements were taken from which to construct a detailed survey of the Aquarius operating area. These data is currently being processed into a high quality precursor survey data product for use with the follow-on mission, NEEMO 19. Furthermore, forward-looking sonar data was gathered to build a feature-based navigation map, and this map was utilized to improve vehicle navigational accuracy during the survey missions. Active and passive acoustic nodes were deployed to further extend navigational accuracy, in particular to geo-locate specific scientific sites of interest to NASA scientists and Aquanauts. Data processing

and sharing and vehicle navigation performance improvement evaluations (due to the Terrain-aided Navigation capability) efforts are ongoing and will be reported at a future date.

For phase 2, new site navigation and semi-autonomous (i.e., sensor-assisted tele-operation) was demonstrated. For site navigation, two control behaviors were implemented and tested (based on Cross-Track Error, or CTE, controller and ‘carrot’ controller, respectively). The operating area experienced high currents (>1.5 kts), and some missions were interrupted for vehicle safety considerations – the Aquarius operating area is a complex, cluttered environment and the hovering platform has a large surface area, making it particularly susceptible to currents. Future research efforts will investigate methods to mitigate this limitation. It was found that the CTE control was inferior in these high-current conditions. Four semi-autonomous modes were implemented to assist the Aquanauts with exploration: Force control, Velocity Control, Dynamic Positioning Control, and Fully Autonomous mission execution. This task required network integration of the THAUS system with the Aquarius network to allow vehicle control from within the habitat via a simple joystick, while providing real-time situational awareness. Unfortunately, this task could not be completed due to a THAUS power system failure at the start of the joint diver-robot operations (after 12 days of operations). The vehicle could not be repaired in the field. Similarly, the diver-assist and mapping tasks could not be completed (due to the same failure) during NEEMO 18, even though the capability exists. These tasks will be completed in September-October 2014.



POC: Dr. Noel DuToit (nedutoit@nps.edu) and Dr. Doug Horner (dphorner@nps.edu)

6. Robotic Outposts to Support Persistent AUV Operations

Autonomous Underwater Vehicles (AUVs) have yet to reach their full potential for undersea warfare operations. Current AUVs (and unmanned systems more generally) require launch and recovery and logistics support from manned surface platforms (e.g., LCS). In combat zones or contested areas, these manned platforms must operate in harms way, which requires additional manned assets for force protection, command and control, air support, etc. The logistics tail required to support unmanned operations in dangerous areas can quickly defeat the purpose of going unmanned in the first place. These surface support requirements are due primarily to current unmanned vehicle deployment methods, and AUVs’ limited energy available for mission execution. If unmanned vehicles could be deployed and sustained without a manned surface platform, the additional logistics associated with supporting and protecting the surface platforms could be eliminated. Thus, before naval forces can fully leverage autonomous vehicles in support of the wide-area, long-duration missions characteristic of undersea warfare, it is necessary to break the tether between the robot and its support by manned platforms. This is particularly true

when operating in denied environments. One concept for achieving increased persistence without burdening manned support vessels is an “undersea garage,” or robotic outpost.

This stationary and/or mobile robotic outpost is intended to be self-sustaining while providing power and communications to untethered AUV assets for vehicle-specific mission execution. In contrast with current unmanned underwater systems, the robotic outpost negates the need for persistent operational and logistics support, thereby enabling covert deployment and continuous AUV operations in denied areas. Ideally, the robotic outpost should be AUV-agnostic and capable of supporting multiple heterogeneous vehicles. Furthermore, there is a need to autonomously deploy the outpost’s associated local infrastructure in order to facilitate reliable autonomous operations. This infrastructure may consist of navigation aids and communications relays to provide reach-back to decision makers. Long-term operations will additionally require periodic inspection, routine maintenance, and possibly even emergency repairs of the local infrastructure, outpost facility, and mobile assets. The robotic outpost must therefore have an organic inspection and intervention capability.

A conceptual underwater robotic outpost is illustrated in the figure below (*see Figure 26*). The proposed robotic outpost can be dropped (or swim) into such a denied region where it can lie dormant until action is required. The outpost is self-sustaining, does not require a surface presence, and overcomes the energy and communication constraints of conventional AUVs. The outpost contains multiple, heterogeneous assets for different mission profiles. The outpost deploys the required navigational infrastructure to ensure robust AUV docking (both overt and covert). Energy is harvested from the environment to power the outpost and recharge the AUV assets, and communication packages (e.g., a retractable buoy) allow for long-range communications with the external world. The outpost’s organic inspection/intervention asset maintains the outpost and associated assets to ensure long-term operation. A basic parts-manufacture and repair facility allows flexible and efficient repair and upkeep. As the global mission evolves, the facility is moved to provide flexible, reliable support.

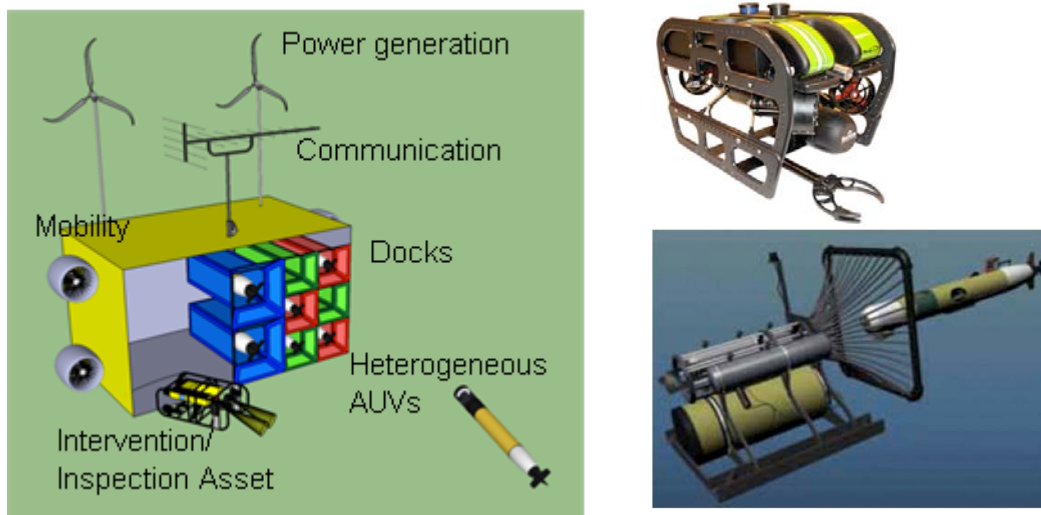


Figure 26. Underwater Garage concept (left), THAUS (right, top), and REMUS 100 with docking station (right, bottom)

This project is aimed at developing and deploying various components of the robotic outpost concept. This incremental deployment will allow CAVR researchers to investigate relevant challenges associated with autonomy, navigation, perception, and environmental effects on long-term operations in an accessible, ocean-based testbed. Many challenges must be addressed in order to realize this concept, providing a wealth of opportunities for research and experimentation: (i) power generation, storage, and transfer; (ii) communications (both locally and with the outside world); (iii) autonomous docking and other interactions with the robotic outpost, (iv) vehicle navigation and operation over extended periods, (v) maintenance of the outpost infrastructure and autonomous vehicles, (vi) infrastructure monitoring, surveying, and deployment, and (vii) outpost mobility, to name a few. The 2-year effort addresses aspects of items (i) – (vi) while leveraging ongoing CAVR research efforts (below).

Tethered Hovering Autonomous Underwater System (THAUS) is a CAVR research platform, which was developed for close-quarters underwater operations. In the context of the underwater garage, this platform performs support tasks at a robotic outpost such as site preparation and infrastructure deployment, robotic outpost monitoring and maintenance, and docked AUV inspection and maintenance. THAUS is based on the SeaBotix vLBV300 miniROV (*see Figure 26*) and is operated in autonomous or semi-autonomous mode.

The Monterey Inner Shelf Observatory (MISO) facility is located 300 yards off Del Monte Beach in Monterey, CA at a depth of ~17 meters. The facility consists of an in situ power and communications node, providing unlimited shore power for recharging vehicles and real-time data access to researchers on the NPS network. Additionally, CAVR is extending the in-situ facility with active and passive acoustic beacons to address the challenges associated with navigation and docking in a realistic ocean environment. This Underwater Experimentation Arena (UEXA) bridges the gap between test-tank development and ocean operations.

Year 1 research objectives included: persistent AUV operations, information sharing between THAUS and REMUS, and infrastructure deployment with THAUS.

CAVR integrated a REMUS 100 underwater docking station (*see Figure 26*) with MISO, leveraging the power and data connection. An interface between MISO and CAVR systems was designed and installed (*see Figure 27, top*). The docking station was deployed at the MISO facility in March 2014 (*see Figure 27, bottom*), which provided a baseline persistent presence and basic autonomous docking capability. The organic docking capability is very rudimentary, and relies on a dedicated Ultra-Short Baseline (USBL) acoustic beaconing system. The vehicle requires a known flight path angle and attempts docking at 3 kts. During the experiment, the vehicle docked successfully during 6 of 9 missions. However, a large wave surge shifted the docking station, changing the flight path angle. Furthermore, the aggressive docking maneuvers damaged the docking station as well as the REMUS. As a result, CAVR is improving docking performance by integrating more navigational sensors with the active beaconing system and the vehicle's cross-body thrusters for a gentler docking maneuver (performed by LT Chase Dillard for thesis research). Furthermore, ENS Jake Jurigo investigated Terrain-Aided Navigation, which utilizes different sources of acoustic information (i.e., forward-looking SONAR-based feature tracking and micro-bathymetry-based terrain navigation) to improve navigational accuracy,

which in turn will be leveraged for docking operations. In addition, CAVR is investigating passive sensor-aided navigation, based on visual servoing, to aid with passive vehicle tracking during the terminal control for the docking maneuver (ongoing work). The passive sensor-aided navigation capability is being developed on the THAUS platform and will be ported to the REMUS platform.



Figure 27: The Electronics Interface between MISO and CAVR equipment, designed, built, and deployed (top), and the REMUS 100 Docking station deployment at MISO and deployed with a docked vehicle (bottom)

The organic docking station and docking maneuver is specific to the REMUS 100. The efforts above are aimed at generalizing the navigation algorithms for such maneuvers, but alternative docking concepts are being investigated that are vehicle agnostic. Mechanical concepts are being investigated that do not rely on physical connections (i.e., wireless data transfer and inductive charging) as part of the Mechanical Engineering Design Class.

The underwater garage concept inherently utilizes different classes and instances of AUVs. One challenge is information sharing between vehicles with dissimilar dynamic and sensory capabilities. During recent field experiments, data was shared between the REMUS and THAUS AUVs. This data sharing does not yet occur in real-time. LT Matt Mitchelson is investigating 3D mapping of complex underwater structures (thesis research), including selective and intelligent information sharing with other assets (e.g., other AUVs or divers) in real-time to facilitate multi-vehicle and joint human-robot mission execution.

Finally, CAVR is investigating autonomous infrastructure deployment for underwater garage operations. As a first step, the acoustic communications topology of the environment must be understood to identify optimal locations for active acoustic networks (for both localization and communication). Such a communications network has already been investigated for the complex, cluttered Monterey Harbor. This capability is being leveraged for the underwater garage infrastructure deployment. Automated techniques are being developed to identify optimal active and passive acoustic node locations to support both a communications network and localization arena for operations around the underwater garage. Simultaneously, autonomous capabilities are under development for dynamic vehicle stabilization during asset deployment and intervention with the THAUS platform, as performed by LT Nick Valladarez (thesis research). The combination of these tasks will provide an autonomous infrastructure deployment capability (Year 2).

CAVR remains on track to meet Year 1 objectives and execute Year 2 tasks, which include: REMUS long-term surveying and mapping, and autonomous mission adaptation (based on environmental changes over time); THAUS navigation aiding infrastructure deployment, outpost and AUV inspection and intervention; and joint REMUS-THAUS operations.

- Demonstrate long-term mapping and environmental change logging utilizing the REMUS platform.
- Automatically adapt the REMUS mission profile based on the evolution of the detected environment.
- Autonomously deploy navigation aiding infrastructure with the THAUS system and build a navigation map of the outpost environment.
- Automatically position THAUS to perform outpost/AUV inspection (human inspector).
- Demonstrate sensor-assisted THAUS tele-operation for outpost/AUV intervention

POC: Dr. Noel DuToit (nedutoit@nps.edu) and Dr. Doug Horner (dphorner@nps.edu)

7. AUV Operations in Extreme, Under-Ice Environments

Researchers at the NPS Center for Autonomous Vehicle Research (CAVR) have recently focused on the Autonomous Underwater Vehicle (AUV) operations in extreme environments; environments where robotic assistive technologies are required, not merely desired. CAVR has 25+ years of experience with underwater operations, but these extreme environments pose significant, unique challenges to AUV platforms. Under-ice operations are one example of such an environment that is of particular interest to the US Navy. Limited under-ice operations have been performed with AUVs, in part due to the harshness of the environments for humans and platforms alike, as well as the technological and operational challenges. Particular research questions that CAVR will be addressing include: quantify the effects of ice-coverage on AUV performance (i.e., navigation and communication); identify platform vulnerabilities for operating

in extreme cold conditions; identify operational challenges for executing AUV missions under ice, and explore novel challenges associated with human and scientific exploration under ice. CAVR is exploring under-ice AUV operations with an incremental execution plan that culminates in participation with ICEX16. Some of the challenges include: cold-weather operations, under-ice localization and navigation, acoustic mapping of the environment, under-ice vehicle launch and recovery, diver assistance and monitoring, and asset location and recovery with an AUV.

The original proposal aimed at under-ice operations at Lake Untersee, Antarctica, in partnership with Dr. Dale Andersen of the Carl Sagan Center at the SETI Institute, in October-December 2014. However, CAVR has determined that a multi-year, incremental approach is required to maximize the probability of mission success. A multi-year experimentation plan has been developed that starts with ice-free operations in an isolated water body, followed by under-ice operations at the same water body, before transitioning to under-ice operations in a remote location and finally ICEX16.

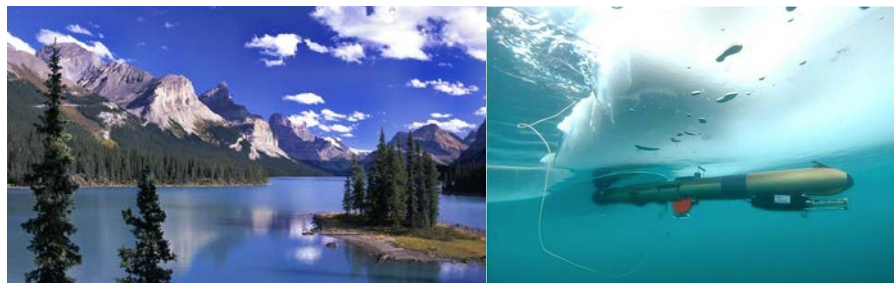


Figure 28: Pavlion Lake, BC and under-ice AUV operations at Pavlion Lake²

Phase 1 – Ice-free operations: In order to understand the effects of ice coverage on vehicle performance and mission execution, a baseline operation is required. Pavilion Lake in British Columbia, Canada has been identified as an ideal location for initial ice-free and subsequent under-ice operations. The lake is accessible year-round, freezing over in November-December, but has low snowfall, thus allowing for consistent operations. This relatively small lake contains unique microbial mats that have been studied by NASA and the SETI Institute, resulting in a history of AUV and ROV operations in this lake. This prior experience can be leveraged for logistical support. CAVR will be focusing on mapping missions, acoustic network deployment, acoustic topology identification, and scientific diver/exploration support. CAVR will be performing these missions with specially equipped REMUS 100 AUVs and the Tethered, Hovering Autonomous Underwater System (THAUS), which is being developed by CAVR for close-quarter AUV operations and joint diver-robot task execution. System customization is ongoing, and this fieldwork for this phase will be executed in November-December 2014.

Phase 2 – Under-ice operations with ready reach-back: Once the baseline system performance has been established, CAVR will return to Pavilion Lake for under-ice operations. This work will

² www.dailygalaxy.com, www.auvac.com

be done in collaboration with Dr. Dale Andersen, who has extensive expeditionary experience through his research group (including operations in Antarctica since the 1970's). The same objectives will be executed (mapping, communications, navigation, diver support), which will allow CAVR to understand the effects of the ice cover on vehicle performance. In addition, strategies for leveraging the ice for navigational purposes will be explored (e.g., terrain-aided navigation using both the ice and lake bottom, etc.). Furthermore, CAVR will gain experience with under-ice operations and the effects of the harsh climate on the vehicles and support equipment. Notably, this experience will be gained at a relatively accessible location, allowing reach-back in case of system failure. This phase will be executed in February 2015.

Phase 3 – Remote under-ice operations. Lake Untersee, Antarctica is of significant scientific interest due to its isolation and the biology contained therein. As per the original proposal, CAVR will use a REMUS 100 and the Tethered, Hovering Autonomous Underwater System (THAUS) to support the science mission. However, all of the techniques and capabilities developed during this research transfer directly to Naval operations. Specifically, the REMUS 100 will be used to perform bathymetric surveys of the ~11 km² lake and further investigate localization and communication challenges, based on experience at Pavilion Lake. The THAUS will be used for diver support, to map the water-glacier interface, and intervention/recovery techniques. By collaborating with Dr. Andersen, CAVR leverages the extensive expeditionary experience of his research group (which has been operating in Antarctica since the 1970's) and resources to significantly reduce mission overhead and risk. This phase will be executed in October-December 2015.



Figure 29: Human under-ice operations at Lake Untersee, Antarctica³

Phase 4 – Under-ice operations during ICEX. NPS CAVR has been invited to participate in ICEX16. Operational and technological objectives are still being defined, but will leverage and extend CAVR's under-ice operational experience and specialized AUV platforms.

CAVR is currently executing *Phases 1-2* through CRUSER support, in collaboration with NASA Ames (Dr. Darlene Lim), NASA Johnson Space Center (Dr. Andrew Abercrombie), and the

³ Images courtesy of Dr. Dale Andersen

SETI Institution (Dr. Dale Andersen). Vehicle modifications are currently being performed to allow under-ice operations in these harsh conditions. Solutions are being developed and tested for vehicle deployment and recovery (LT Chase Dillard thesis work), as well as providing diver assistance and asset recovery (LTJG Jose Alberti and LT Nick Valladarez theses work). Technological solutions have been developed to map the communications topology during ice-free and under-ice operations (Dr. Horner). Furthermore, technological solutions have been developed that combines feature-based navigation (i.e., using forward-looking sonar to track acoustic landmarks in the environment) and terrain-aided navigation (i.e., using downward looking micro-bathymetry sonar and a prior survey map) for improved navigational accuracy (ENS Jake Juriga thesis work). This work will be extended for simultaneous upward (ice-relative) and downward (bottom-relative) navigation. Ongoing work is addressing high-resolution 3D mapping using a hovering AUV (LT Matt Mitchelson thesis work).

POC: Dr. Noel DuToit (nedutoit@nps.edu) and Dr. Doug Horner (dphorner@nps.edu)

8. Development of Very-Small Multi Rotor Aircraft as Platforms for Atmospheric and Sea Surface Measurement

The objective of this research is to develop new technologies that will improve the ability of the US Navy to characterize the physical environment and enhance Battlespace Awareness. Of particular importance to the US Navy is quantifying meteorological and electromagnetic (EM) propagation and electro-optical (EO) conditions in the lower atmosphere and providing input for numerical weather forecast models.

Introduction and Background

Due to the cancellation of the Navy's radiosonde (weather balloon) program, there is currently a gap in the Navy's ability to detect low-level atmospheric features such as the evaporation duct. One possible way to fill this gap in a cost-effective manner is through the use of inexpensive very small Multi-Rotor Vertical Takeoff and Landing (MR-VTOL) unmanned aircraft for routine and special measurements of low-level atmospheric properties, including those that are relevant to EM/EO propagation and small boat or periscope detection.

There is very little published research on the use of MR-VTOL unmanned aircraft as meteorological platforms. Therefore, we were not sure how feasible or accurate such measurements would be. This research addressed that lack knowledge by performing a series of tests of a measurement system consisting of a radiosonde attached to a MR-VTOL, in this case the InstantEye Mark 2 Gen 3, manufactured by Physical Sciences, Inc. (see *Figure 30*). In particular, we sought to quantify the accuracy of the measurements and analyze the errors induced by rotor wash, solar and long wave radiation contamination, sensor exposure, platform movement and other factors.



Figure 30. InstantEye MR-VTOL unmanned aircraft with radiosonde attached.

Experiment Description

This MR-VTOL/radiosonde system was flown alongside a calibrated meteorological tower with temperature and humidity sensors located at six or seven levels, from 16 cm above the surface to 5m elevation (*see Figure 31*). By comparing the MR-VTOL/radiosonde measurements with the tower measurements, the accuracy of the MR-VTOL/radiosonde was quantified. Also because there was a gradient in the potential temperature (temperature adjusted for altitude) during the time of the experiments, it was possible to determine how much the rotor wash moved the air (on average) up or down from the elevation of the MR-VTOL. Another potential problem with this type of measurement is contamination from natural solar or terrestrial (longwave) radiation. Radiation effects are typically minimized by placing radiation shields over and using fans to aerate the sensors; this was the method used for the calibrated tower measurements. A radiation shield was not practical for the MR-VTOL platform measurements. However, the movement of the air due to the rotors does provide a good airflow past the sensors, counteracting the need for radiational shielding. Another technique to increase airflow past the sensors was to move the MR-VTOL horizontally (normally it hovered at a particular level). We also examined how measured pressure on the sensors is affected by ground effects.



Figure 31. InstantEye/Radiosonde alongside

Results

Time Series and Short Term Fluctuations.

Comparing time series of the MR-VTOL/Radiosonde temperature measurement vs the tower (not shown) showed that the MR-VTOL/Radiosonde measurements had considerably more variation than the tower measurements. However, the tower had larger temperature probes that responded much more slowly to temperature variations than the sensors on the radiosonde (20 second response time vs 2 seconds). The significant short-time-scale variations in temperature did not exist when the MR-VTOL/Radiosonde was at 300 m elevation above the surface, providing evidence that the variations were not caused by rotor wash effects, but rather natural turbulent fluctuation in the actual air temperature near the surface. For a subsequent experiment (just performed one week before this report was written and results not yet analyzed) we placed a fast-response temperature probe on the tower. This will allow us to verify with certainty that the large fluctuations we observed near the surface are real and not just rotor-induced.

Bias and RMS Errors

The results of MR-VTOL/Radiosonde vs tower temperature measurements for a 90 minute flight (see Table 7) showed that the average (bias) and root-mean-square (RMS) errors generally decreased with elevation. At the highest level (Level 6, 3 meters above the surface in this case) the average (mean or median) difference between MR-VTOL/Radiosonde and the tower was less

than 0.1 C. The RMS difference was 0.2 C, when averaged over 20 seconds. Levels 3–6 had a warm bias for the MR-VTOL/Radiosonde, while level 1 had a cold bias. Because during this period the potential temperature decreased with elevation, these results indicate that for Levels 3–6, the air passing over the sensors originated from an elevation lower than the sensors.

Table 7. Bias and RMS Error Summary*

Level	# of samples	Mean (C)	Median (C)	RMS [#] (C)
1	71	-0.27	-0.26	0.53
3	118	0.68	0.72	0.76
4	108	0.35	0.34	0.32
5	176	0.27	0.12	0.37
6	91	0.09	-0.03	0.20

**Statistics based on air temperature (C) as measured by the MR-VTOL/Radiosonde minus the air temperature as measured by the calibrated tower sensors.*

[#]RMS = Standard Deviation of difference using 20 second running average

Apparently the air below the MR-VTOL/Radiosonde is replaced by the rotor wash air and loops around and above the MR-VTOL/Radiosonde before passing over the sensors. When hovering at Level 1 (only 16 cm above the surface) there is not enough air volume below the sensor to push air up and around and instead the air passing over the sensors at this elevation originates above the MR-VTOL/Radiosonde.

Other Results Concerning Temperature Measurement Accuracy

(1) To test the theory that sideways motion will bring “cleaner” air over the sensors, we compared measurements when the MR-VTOL/Radiosonde was hovering in place vs. measurements when the MR-VTOL/Radiosonde was moving sideways. There was no significant difference, indicating hovering measurements are just as accurate as “moving sideways” measurements.

(2) Different wind speeds did not appear to affect the measurement errors, at least up to the 4 ms⁻¹ maximum wind speed that was present during the tests.

(3) When the MR-VTOL/Radiosonde was manually held in place with the rotors turned off, there was a 0.5 to 2.0 C warm bias due to solar radiation contamination. This shows that in terms of reducing radiation effects, the rotor wash was necessary to prevent radiation contamination.

Ground Effect Dynamic Pressure

The pressure started to increase more than would be expected naturally when the MR-VTOL/Radiosonde was below about 1.5 meters above the surface, due to the dynamic pressure

induced when the rotor wash “squeezes” the air below it against the ground. This effect was largest just above the ground (16 cm) where the ground effect of the rotor wash increased the pressure by 0.6 hPa which corresponds to a 6 m change in elevation.

Other Results

The author also evaluated other aspects of using the MR-VTOL/radiosonde system for Navy use. This system is inexpensive (\$6000 for a complete system including control station, 2 birds and spare parts), easy to set up (typically less than 5 minutes), easy to fly for unexperienced pilots and able to take-off fly and land safely in windy conditions (at least less than 10 ms⁻¹). This would be a suitable system to use for low-level atmospheric sampling from ships. One major weakness is that flight time must be less than 25 minutes due to battery limitations. Therefore this system could not be used to sample horizontal variations in the atmosphere or fly higher than about 5000 feet above the surface.

One of the main difficulties encountered in this research was getting the required NAVAIR interim flight clearances (IFC) which are required (but often ignored) for operating any unmanned aerial system (UAS) in a Navy setting. Even though the InstantEye is very small and therefore quite safe, the procedure for getting IFC was expensive and time-consuming. Currently there is no IFC for flying the MR-VTOL/radiosonde or other meteorological platforms from ships. This limits the ability of scientists and engineers to test various systems for Navy use.

Conclusions

To the author’s knowledge, this research is the first time the accuracy of using MR-VTOL aircraft for meteorological measurements has been quantified. MR-VTOL/Radiosonde measurements near the surface are strongly affected by turbulent fluctuations during sunny, low wind days over a dry surface. To obtain accurate mean values of air temperature and humidity, the air should be sampled for 1 to 5 minutes at the same elevation. The rotor wash (1) provides sensor aeration which counteracts radiation contamination effects, (2) creates dynamic pressure effects in the lowest 1.5 meters and (3) moves air from different levels. By quantifying effects (2) and (3) we are able to correct future measurements and increase measurement accuracy. Horizontal motion of the MR-VTOL/Radiosonde had little effect on the measurements. Above 1.5 meters elevation, the temperature accuracy was 0.2 to 0.3 C if samples are obtained at the same location for at least 1 minute. Below 1.5 m elevation, the temperature measurements are not as accurate due to the mixing effects of the rotors. Above the turbulent atmospheric surface layer (usually > 50 m elevation) the temperature measurements are more accurate, and less time averaging is required.

Several more tests under varying atmospheric conditions were performed; the analyses of these data sets are ongoing. Therefore the conclusions on measurement accuracy should be considered to be preliminary. However we can conclude that the MR-VTOL/Radiosonde measurement method can provide temperature and humidity measurements that are accurate enough for the US Navy to use for determination of EM propagation conditions and for input into forecast models.

Unlike manned and fixed wing aircraft, the system described here can sample very low to the surface, which is important for quantifying the effects of features that affect RF transmissions such as the evaporation duct.

To summarize, the MR-VTOL/Radiosonde system described could provide measurements that are accurate enough for Navy purposes and are especially useful for very low level measurements that cannot be performed accurately directly from ships due to ship contamination effects and are too low for safe fixed-wing UAS and manned aircraft measurements.

POC: Dr. Peter Guest (pguest@nps.edu)

9. A Tele-Operative Sensory-Motor Control Platform (TSMCP)

A research summary was not available for this project at the time of report distribution. The Departments of Systems Engineering and Physics at NPS have teamed with Naval Research Laboratories (NRL) to develop a tele-operative sensory-motor control platform (TSMCP) that enables tele-manipulation of objects in inaccessible or dangerous environments. Although remote operation of robotic manipulators is a maturing field in commercial, security, and medical arenas, a system capturing both arm and hand dynamics has yet to be achieved that is robust enough for field use, yet precise enough for delicate operations. Furthermore, the challenges of autonomous vehicle operation when supporting an operator controlling robotic arms has received limited attention in robotics research. Our goal is to establish a hardware platform for use in research experiments and laboratory teaching exercises related to the design, testing, and implementation of tele-operation subsystems that will provide a unique education experience and support future full system development.

Equipment and pilot results in this study will be used to design a set of teaching laboratory experiments on manipulator dynamics, human-robot interface, sensory-motor integration all within the context of robot tele-operation. Equipment and time in this program will be used to leverage future funding for full system development (with international collaboration) with the long-term aim to establish NPS as a leader in this field. Program findings will elucidate fundamental principles, as well as build on and establish new international and commercial collaborations for future work.

POC: Professor Richard M. Harkins (rharkins@nps.edu) and Dr. Ravi Vaidyanathan (rvaidyan@nps.edu)

10. Tropical Cyclone Reconnaissance with the Global Hawk: Assessment of Initial Results and Use in Improving Forecasts of Tropical Cyclone Intensity and Structure

A research summary was not available for this project at the time of report distribution. This project used the Global Hawk aircraft for tropical cyclone reconnaissance is investigated. Under previous CRUSER support, M.S. theses emphasized the unique capability of the Global Hawk to potentially improve forecasts of tropical cyclone intensity and structure, which address significant operational requirements. Subsequently, two Global Hawk aircraft operated by the National Aeronautics and Space Administration (NASA) have been used to obtain observations in tropical cyclones over the Atlantic Ocean. Additionally, a new department research initiative has been funded by the Office of Naval Research, Marine Meteorology Division (ONR/MMD) and new project is being proposed to NASA to extend the Atlantic Global Hawk observation project with a similar project over the western North Pacific.

This project addresses two primary objectives. The current use of the Global Hawk over Atlantic Ocean tropical cyclones is examined for improvement of intensity and structure forecasts. Second, the operational weather commands, operational reconnaissance commands, science laboratories, and relevant civilian institutions are engaged to shape the use of the Global Hawk in the western North Pacific with the objective of improved operational support to shore-based and afloat operations throughout the western North Pacific.

The project design provides an opportunity for Naval Postgraduate School (NPS) graduate students in the Meteorology-Oceanography (METOC) curricula to draw upon their previous operational experience to define strategies, capabilities, and applications that result from Global Hawk operations over tropical cyclones. Significant student interaction with United States Navy and Air Force commands, NASA, and international organizations is anticipated. It is expected that several M.S. theses will result from this project with topics ranging from assessment of Global Hawk observations on intensity and structure forecasts to logistical and operational strategies of the use of a Global Hawk in the environment of the western North Pacific.

POC: Dr. Patrick Harr (paharr54@sbcglobal.net)

11. Short Range Radiative Wireless Power Transfer (WPT) for UAV/UAS Battery Charging

There are numerous advantages of wireless power transfer (WPT) for many remote energy source and battery charging applications. Recently, WPT has been used for charging wireless devices, and commercial WPT charging products have appeared on the market.

The basic block diagram of a WPT system is shown in Figure 32. Prime power is provided by the base station converted to radio frequency and then input to a coil or antenna. On the client side the received power is conditioned and subsequently delivered to the battery or power plant.

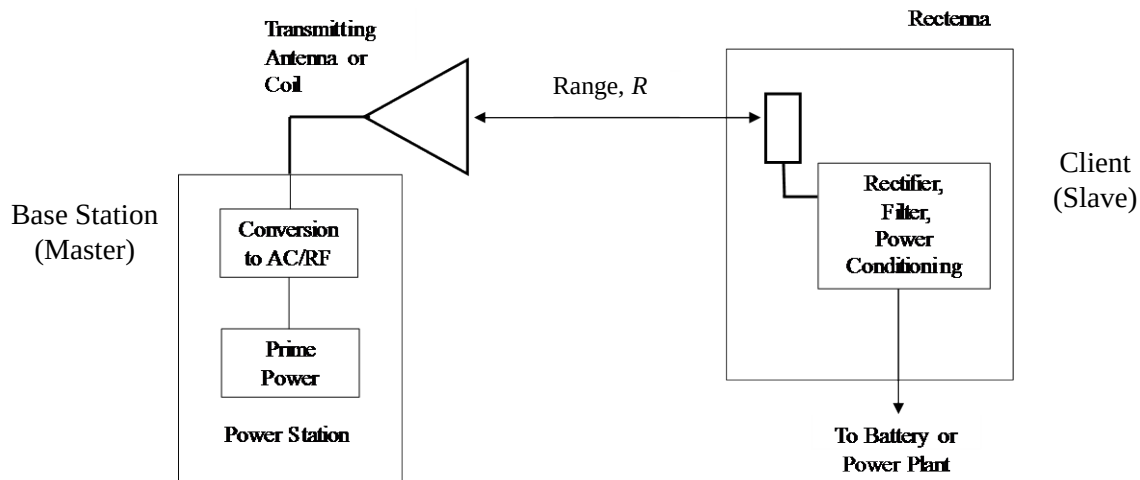


Figure 32. Block diagram of a WPT system.

For short ranges (less than a couple of cm) *inductive WPT* systems are viable. Inductive systems use two coils as shown in Figure 33 with one located in the charging station and the second in the device. Energy is transferred by the magnetic fields linking the coils. At the receiving coil, circuits are required to rectify and condition the output voltage for charging the battery. Generally it is not possible to compute the flux Φ_{21} except for some very simple cases. However, electromagnetic simulation software is capable of numerically solving for the currents and voltages in the WPT circuit.

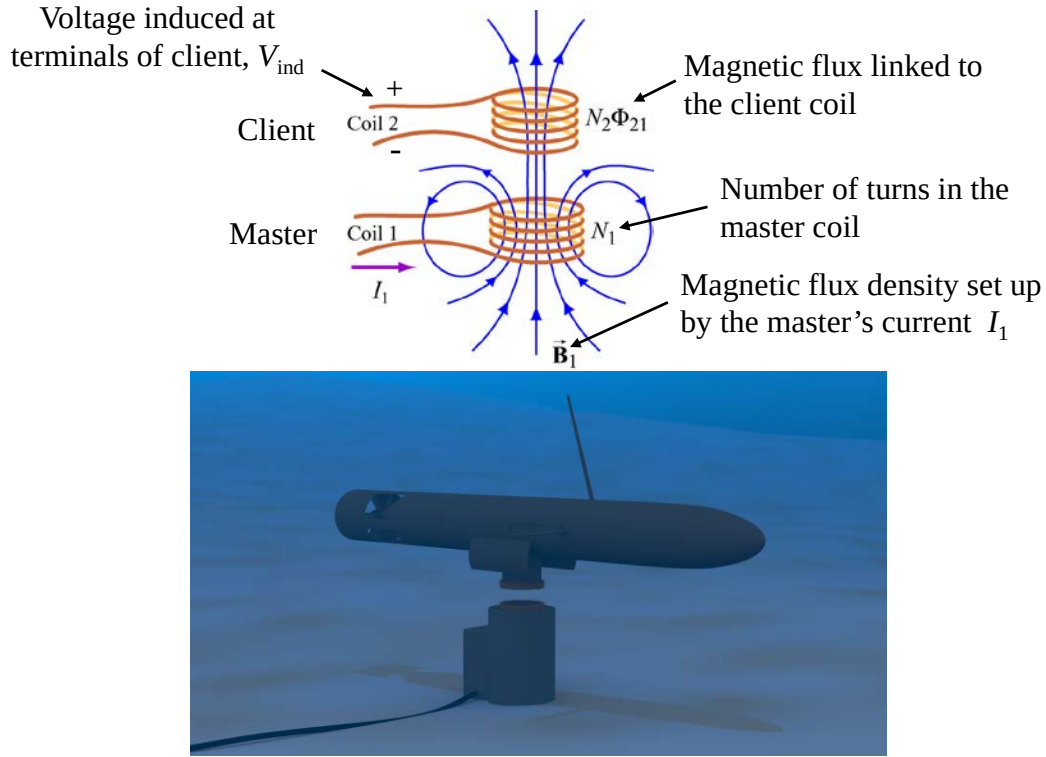


Figure 33. Principle and application of inductive power transfer.

Inductive systems generally operate at low frequencies (< 10 MHz and usually in the hundreds of kHz range). Efficiencies greater than 75% are routinely achieved, with some systems achieving efficiencies greater than 95%, however, they operate at very short ranges (several mm) and alignment of the coils is critical.

Radiative WPT systems use two antennas rather than coils, and the energy is transferred by a propagating wave. The received power at antenna separation R is given by:

$$P_r = \frac{P_t G_t G_r \lambda^2 L}{(4\pi R)^2} |F|^2 \quad (1)$$

where P_t is the transmitted power, G_t the charging station antenna gain, G_r the receiving (client) antenna gain, and $\lambda = c/f$ is the wavelength (c is the speed of light, f is the frequency in Hz). F is a factor that accounts for wave propagation effects in the medium. L is a system loss factor that includes device losses, rectifier efficiency, etc. The receiving side antenna has an integrated rectifier, and is called a rectenna.

Radiative systems operate at higher frequencies than inductive systems (> 1 GHz), and suffer a $1/R^2$ propagation loss. Higher gain antennas can be used to increase the received power, but high gain antennas become prohibitively large. The use of antennas has advantages though. Solid state array antennas allow full control of the antenna excitation, which permits scanning

and focusing of the beam. This capability relaxes the alignment requirements between the two antennas.

A disadvantage of radiative systems is that they are more susceptible to losses in the medium. This approach cannot be used for vehicles submerged in water or buried in wet ground. However, it can be used for ground vehicles, air vehicles on the ground, or even warfighter packed equipment. It does not require the precise alignment of the charging station and client, and can be designed to operate at distances of several meters or more.

Other issues that must be considered when using electromagnetic energy are safety and interference. However, because of the short ranges and relatively low power involved, safety should not be an issue. Both types of systems can cause interference in neighboring electronic systems.

Inductive WPT Summary

We have investigated an inductive WPT system for charging underwater vehicles. The concept has been studied previously by SSC Pacific in San Diego.⁴ It is a short range (< 4 cm) system that operates at 100 kHz. The low frequency is dictated by the requirement that the system operates efficiently through seawater.

There are various types of compensation networks that can be used. We have selected the series-series approach shown in Figure 3 because of its simplicity, and it is the topology used by SSC Pacific.

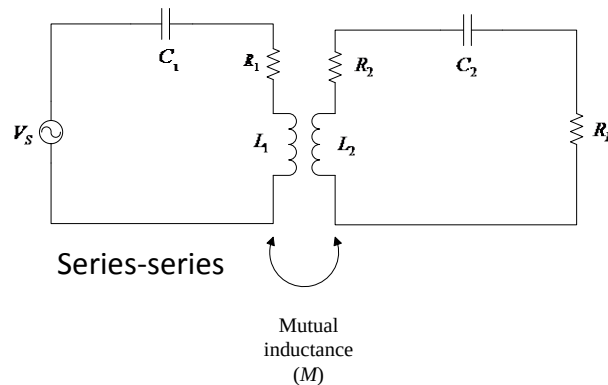


Figure 34. Equivalent circuit of the inductive WPT system.

The efficiency is the power delivered to the load relative to the power transmitted is

⁴ V. Bana, G. Anderson, L. Xu, D. Rodriguez, A. Phipps and J. Rockway, "Characterization of coupled coils in seawater for wireless power transfer," SPAWAR, San Diego, CA, Tech. Rep. 2026, 2013

$$\frac{P_L}{P_t} = \frac{R_L (\omega_0 M)^2}{R_1 (R_2 + R_L)^2 + (\omega_0 M)^2 (R_2 + R_L)} \quad (2)$$

where $\omega_0 = 2\pi f$ and M is the mutual inductance between the transmitting and receiving coils. There is an ideal matched load resistance for a given coil spacing. The matched load changes with distance through M , which is not easily computed, and therefore must be determined by simulation or measurement.

Several commercial software packages can be used to simulate the WPT circuit and coils. CST *Microwave Studio* was selected. The MWS model is shown in Figure 35(a). The coils are backed by plates and have cores. The plates and cores are shown in blue, which is set as free space initially to model the coils in air. The computed efficiency is shown in Figure 5(b) for the coils in air with a spacing of 16 mm (face to face). The computed optimum load value is 29Ω . From the simulation data the optimum appears to be about 45Ω . Measurements were performed in the NPS Microwave Laboratory by masters student J. Cena.⁵ At 16 mm spacing the simulated and measured data are in close agreement, but both are slightly below the calculated value.

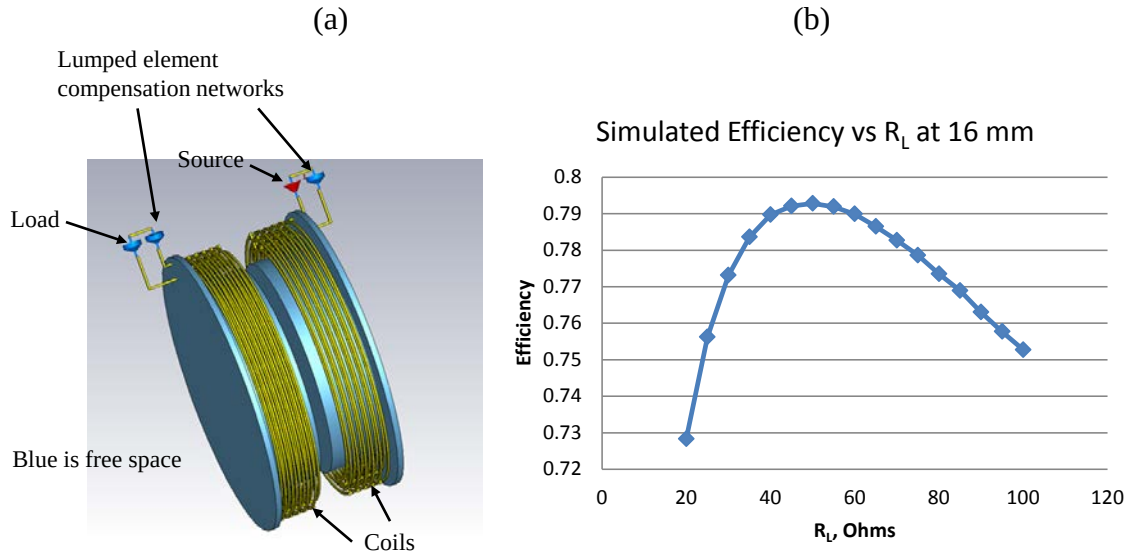


Figure 35. (a) CST MWS model of the WPT coils in air, and (b) simulated efficiency versus load resistance.

A way to confine the magnetic flux and increase coupling is to add a ferrite surface behind the receiving coil. MWS simulations were performed with ferrite plates and cores. A sample of the results is shown in Figure 36. The simulations can be used to find the optimum load resistance from the peaks of the efficiency curves. Note that the efficiency is improved using both the ferrite plates and cores. Measurements were taken by Cena with ferrite plates behind the

⁵ J. Cena, "Power Transfer Efficiency of Mutually Coupled Coils in an Aluminum AUV Hull," Masters Thesis, Naval Postgraduate School, December 2013.

receiving antenna. The measured data also showed an increase in efficiency using the tiles compared to air.

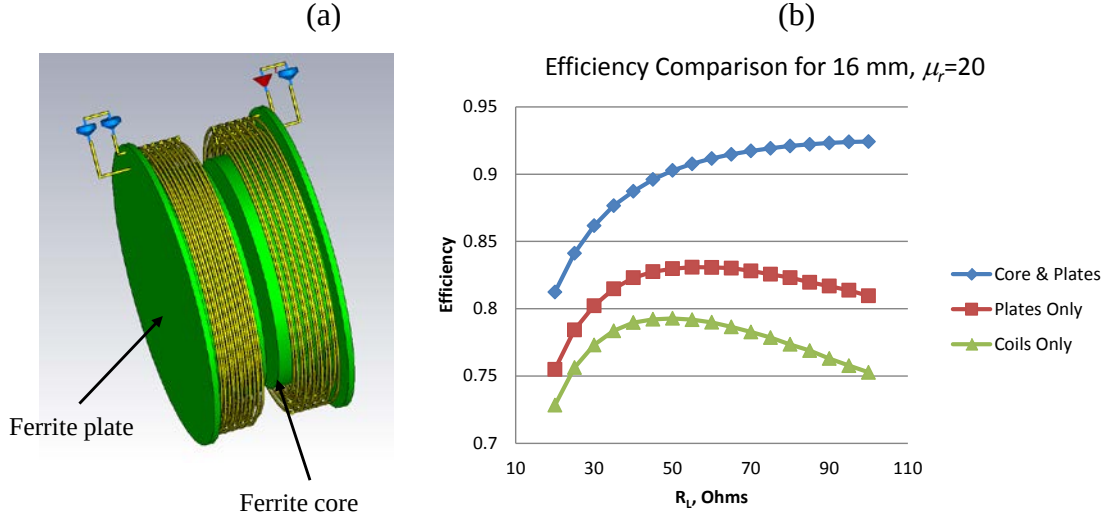


Figure 36. Simulation results (b) for coils with ferrite cores and plates (a).

Radiative WPT Study

In a radiative system, the master station transmits a propagating electromagnetic wave to the client. Generally the master station has a high gain antenna that must be continuously pointed in the direction of the client. This type of WPT has been proposed for numerous applications such as battery charging, spacecraft recharging and station keeping, and direct propulsion of UAVs. The client antenna is usually of low gain and small physical size because it often operates on a mobile platform.

Equation (1) governs the received power versus the system parameters. At close distances the antennas may be in each other's near field and the full gain of the antennas will not be achieved. If the master station antenna is an array with full amplitude and phase control, then near-field focusing can be used. Referring to Figure 6, let the array focal point be at $\vec{r}_f(x_f, y_f, z_f)$ and the observation (field) point at $\vec{R}(x, y, z)$. (Note that here R is not a resistance.) The array is located in the x - z plane and has a rectangular grid with N_x by N_z elements spaced d_x by d_z .

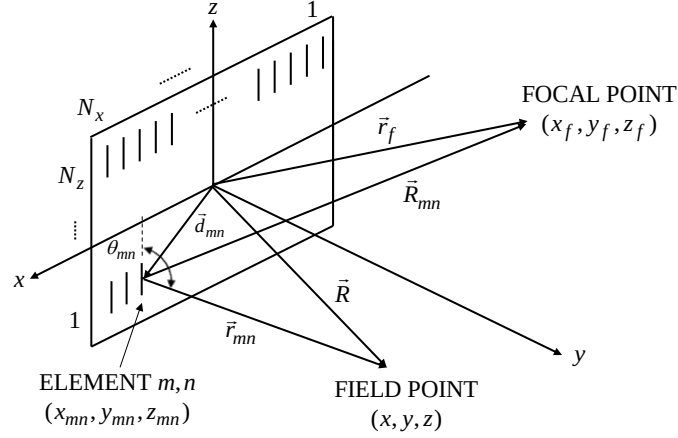


Figure 37. Planar array antenna near field model.

For vertical dipoles at height h above a ground plane the total array field at the observation point is given by

$$\vec{E}(R, \theta, \phi) = j120 \hat{z} \sum_{m=1}^{N_x} \sum_{n=1}^{N_z} \left\{ \frac{e^{-j\beta r_{mn}}}{r_{mn}} \frac{\cos\left(\frac{\pi}{2} \cos \theta_{mn}\right)}{\sin \theta_{mn}} \sin(\beta h \sin \theta_{mn} \sin \phi_{mn}) A_{mn} e^{j\Phi_{mn}} e^{j\psi_{mn}} \right\} \quad (3)$$

where $\beta = 2\pi / \lambda$, A_{mn} is the element's current amplitude coefficient, ψ_{mn} is a miscellaneous calibration and correction phase, and Φ_{mn} is the phase required to focus the beam at r_f . θ_{mn} is the angle between the element m,n axis and the field point position vector, ϕ_{mn} is the element azimuth angle.

In Figure 38 is plotted the electric field intensity for an array of half-wave dipoles above a ground plane at a grid of observation points. The free space attenuation factor $1/R$ is removed. In Figure 7(a) is shown a plot of the normalized electric field intensity in V/m when the transmit array is focused at 2 m (location of the black stem). In Figure 7(b) the result shown is for the focal point at 2000 m in the array's far field (i.e., not focused). The focused case gives an increase of 3.3 dB compared to the far-field case.

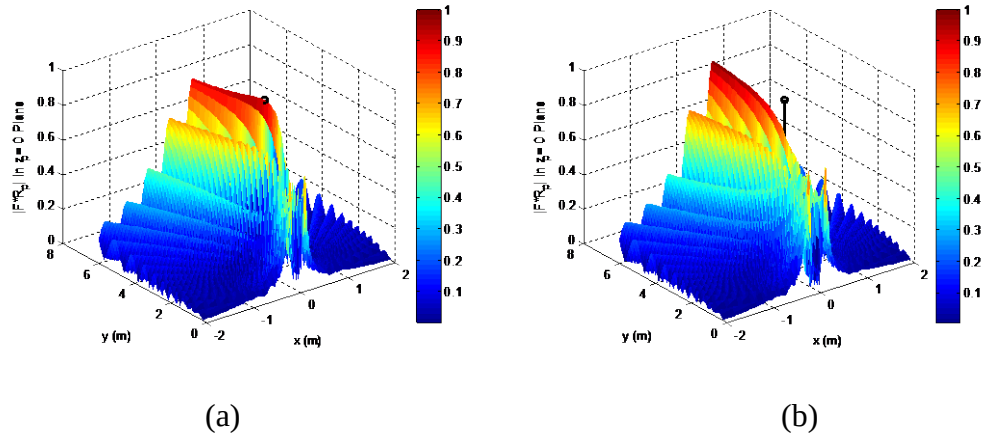


Figure 38. (a) Plot of normalized electric field in V/m when the array is focused at $z = 2$ m and (b) when the array is focused at $z = 2000$ m. The $1/R$ factor has been removed.

Summary

Both inductive and radiative WPT concepts have been analyzed and simulated. Simulations and measurements for an inductive system are in good agreement, and furthermore, simulations indicate that the performance can be improved using ferrite cores and plates. Simulations for a radiative system show that focusing the base station antenna can increase the power to the client.

The next phase of study will concentrate on design and modeling of the compensation and rectifying circuits at the receiving side.

POC: Professor D. Jenn (jenn@nps.edu)

12. Aqua-Quad

This project explores the feasibility of a conceptually new hybrid vehicle that combines a Multi-Rotor Vertical Takeoff and Landing (MR-VTOL) aircraft with a water-tight electronic bay, exchangeable sensor suite and a solar recharge system in order to provide long endurance sensing in mixed terrestrial and aquatic environments to support a multitude of military and civilian missions.

Typically VTOL aircraft are limited to fairly short endurance missions due to the requirement of better than 1:1 power to weight ratio for flight. However, using modern high efficiency monocrystalline Silicon solar cells and rechargeable Lithium batteries, the mission endurance for the vehicle can be extended indefinitely, flying when necessary, but sitting or floating most of the time while performing sensing tasks.

A typical envisioned scenario would include a flock of vehicles that might be outfitted with a specific set of sensors, and dispersed in a grid over the sea surface to search for undersea objects of interest. The first vehicle that picks up a signature might pop-up in the air high enough to form a network with nearby vehicles in order to perform real-time information exchange on the target

with nearby manned or unmanned surface or airborne assets. Vehicles in the flock could take turns flying and sensing to overcome the flight-endurance limitation, and during times of flight, they may relocate using a leap-frog approach. They may also fortuitously utilize the propelling power of local currents thus minimizing the energy required for repositioning. The use of mesh networking technology would make the information exchange secure and transparent to the registered user.

Approach

This was necessarily a platform-design project, as no such hybrid vehicle currently exists, and the performance characteristics of such a vehicle were largely unknown. Like most robotics platforms, it is a system of systems, but the requirement of flight and the constraint of having to harvest all utilized energy from the environment significantly increase the interconnectedness of the various sub-systems. The primary systems include the airframe, flight controls, energy storage and energy harvesting. Progress on each of these is briefly addressed in the sections below.

Airframe: The airframe includes the structure and components necessary for propulsion. In general, multi-rotor craft are quite simple in this respect. For the most part, flight loads are small, as propulsion is distributed amongst the motors, and all propulsive loads are aligned with the z body axis. The Aqua-Quad will be subject to additional structural loads do to the necessity to float and survive rough sea states, and of course it must have a water-tight cabin to house any electrical components that must remain dry.

The notional design utilizes a composite skeleton made from a mix of carbon fiber and printed plastic components. As with anything that flies, weight is paramount. Significant efforts have been made to reduce structural weight, as theory indicates a very strict correlation between weight and power required for flight. The general term used for hovering devices is the Figure of Merit (FOM) which is typically on the order of about 10g/W for aircraft in this class. A CAD drawing of the prototype structure is shown in Figure 39.

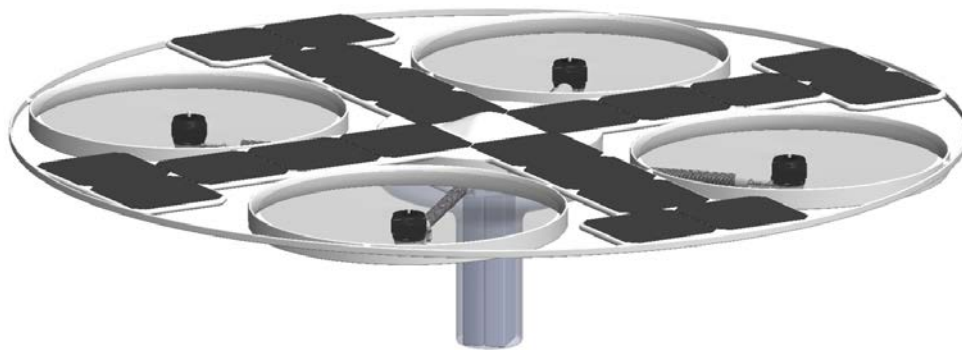


Figure 39: CAD drawing of the prototype Aqua-Quad model including 20-cell solar array, propeller guards, and submersed battery bay.

Sizing of the prototype vehicle was intentionally minimized, with just enough capacity to demonstrate the capability with basic sensing and communication functions. To keep the costs down, the model was designed around un-cut solar cells which were roughly 125mm square. This set the minimal spacing between the 4 motors, and suggested an ideal propeller diameter of about 350-380mm. A search of suitable motors turned up two likely candidates: the T-motor MN3510-13 and the T-Motor U3. According to the manufacturer, they both have similar performance, but in order to better characterize them, a motor test stand was constructed, and a summer intern instrumented the test rig to measure voltage, current, RPM and motor and speed control temperatures while stepping through the full throttle range. The system is fairly automated, using an Arduino Deu to drive the speed control and log all the data sources. The intern-developed software monitors power and temperatures and terminate a session if any of them exceed prescribed limits. The motor test stand is shown in Figure 40, with sample data shown in Figures 41 and 42.

In Figure 3, a propeller is characterized by plotting RPM versus thrust for various running voltages. It is expected that propeller performance is independent of motor voltage, and indeed it appears to be. In Figure 4 the entire propulsion chain is characterized by plotting the Figure of Merit (FOM) versus generated thrust. The FOM is a dimensional parameter typically used to measure hover performance, in this case with units of grams of thrust over Watts of power. Plots for a range of suitable voltages are included, with lower voltages yielding very slight improvements in FOM. The FOM by itself can be misleading, as it appears to indicate outstanding performance at low thrust. To make the data more meaningful, the weight of the motor, propeller and speed control can be subtracted from the thrust, essentially plotting FOM versus *useful thrust*. Here it can be seen that the adjusted FOM is optimal over a fairly large range, in this case roughly 500 to 1000g. The weight of the propulsive hardware is roughly 170g, so this indicates that the motor is optimal providing about 670 to 1170g of thrust. For the quad-rotor that would correspond to full system weights of about 2.5 to 4.7kg.



Figure 40: Motor test stand instrumented by summer intern, Kevin-Patxi Le Bras.

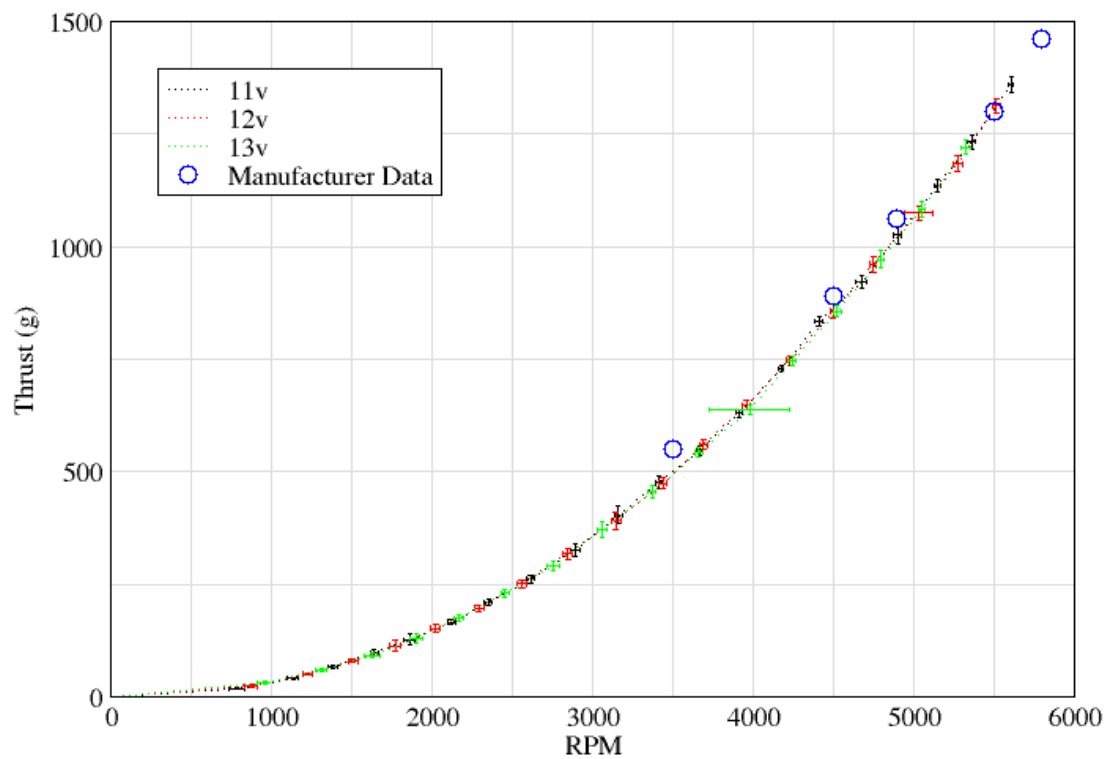


Figure 41: Thrust versus RPM for the T-Motor U3 motor with a T-Motor 14 x 4.8 propeller and Castle Creations Talon 35 electronic speed control. Blue circles are data points extracted from the T-motor website. The error-bars indicate a standard deviation for each 30-second run. The few very large errors in RPM are due to a sensing glitch that occasionally shows up in the RPM sensor.

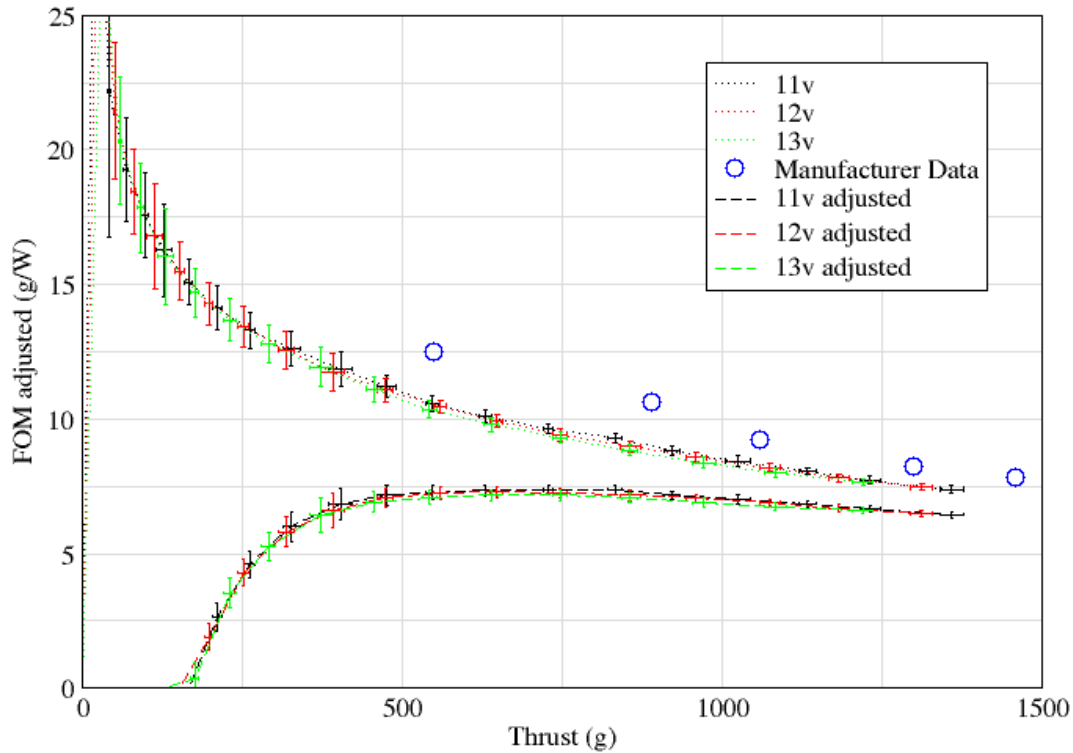


Figure 42: FOM versus thrust for several voltages. See text for the meaning of adjusted measurements. The blue circles represent data points extracted from the manufacturer's website.

Flight Controls: At this point in the project, flight controls have not entered a critical path. Initial prototypes will utilize an off-the-shelf solution, DJI Naza-M V2 with GPS. Later versions will likely progress to the PixHawk to allow for more freedom in automation.

Energy Storage: Lithium polymer batteries are the obvious choice due to both high energy density and high power density. For both this project and the related TaLEUAS project, some work has been done to analyze actual cell performance. There are some available Lithium cells that are claimed to have very high densities, upwards of 220Wh/kg; however, tests using a CBA IV Pro have so far indicated only one cell that actually breaks the 200Wh/kg mark, the GEB 8043125. It is advertised with a 260Wh/kg specific energy, but lab measurements indicate at most 220Wh/kg. While that is still an impressive specific energy, it is important to note that it should not be drained at a rate greater than 1C (this means that all the energy would be drained in one hour), and it has a relatively low lifespan, estimated by the manufacturer at just 50 cycles. These two constraints make the cell unsuitable for this project. The next best cell we have found is the ThunderPowerRC 2000mAh cell, SPB605060H. The cell is advertised with a specific energy of 190Wh/kg, and lab experiments with assembled packs have found actual values in the range of 171Wh/kg, and it can achieve that at drain rates of over 4C (15 minute discharge). This is key for the flight segments of the Aqua-Quad, where the motors will likely drain the battery at 2C to 3C rates, therefore, the ThunderPower cell has been chosen for the project.

Energy Collection: The sole source of energy collection for the Aqua-Quad is photovoltaic through a small array distributed between and around the rotors. The chosen cells (through experience with the TaLEUAS project) are the SunPower research-grade E60 cells. They are semi-rigid, monocrystalline Silicon cells with an advertised efficiency of 24%. The cells are roughly 0.125m square, with slightly cropped cells due to the 160mm diameter wafer they are printed on. As seen in the CAD model in Figure 1, the prototype array size is 20 cells, delivering a nominal peak power of about 73W. The array is connected to an MPPT to optimize panel loading. Several COTS MPPT products are currently under investigation by a summer intern.

Example Scenario:

An ongoing student project simulates a scenario in which four drifting Aqua-Quads with acoustic sensing capabilities are positioned on the surface of the ocean and are tracking a submerged target using bearing-only (similarly with range-only) measurements. The position estimate of the target is determined in two separate ways for later comparison. First, an extended Kalman filter (EKF) is utilized, which linearizes the measurement equations and combines the four bearing measurements into a single position estimate within an ellipse of uncertainty. Next, an unscented Kalman filter (UKF) is used, which omits the linearization step of the EKF through the use of a weighted sampling method and transformation equation. With both filters created, the impact that the relative geometric positioning and number of Aqua-Quads has on the scenario can be evaluated, both in shrinking the positional uncertainty of the target and also in reducing the convergence time of the filter. Sample results are shown in the figures below (*see Figures 43 and 44*).

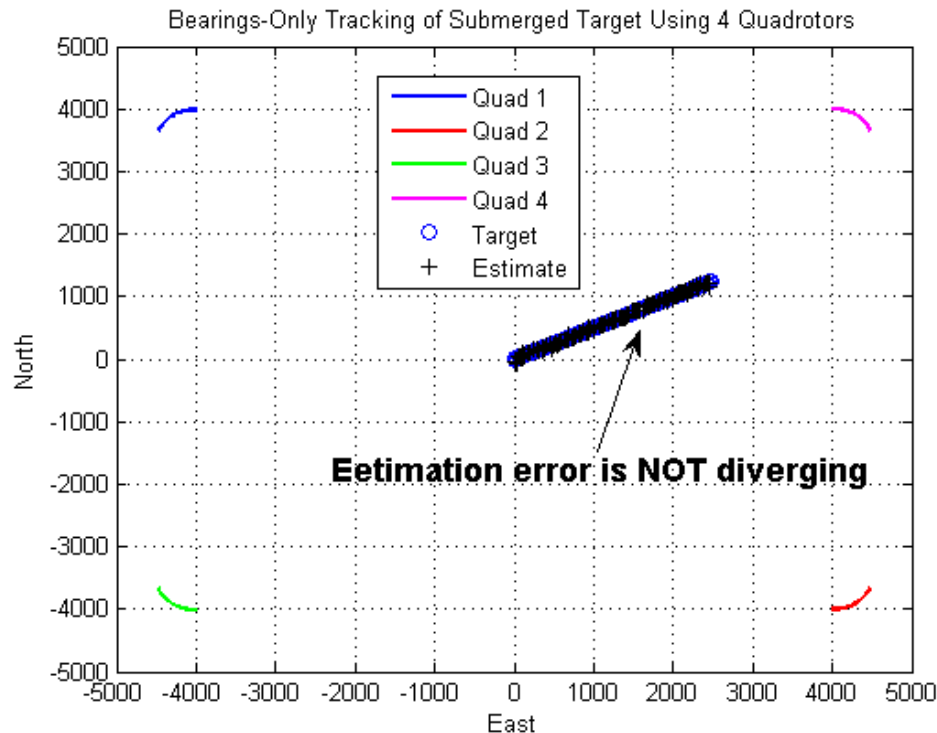


Figure 43: Estimated target trajectory using 4 drifters with passive acoustic sensors.

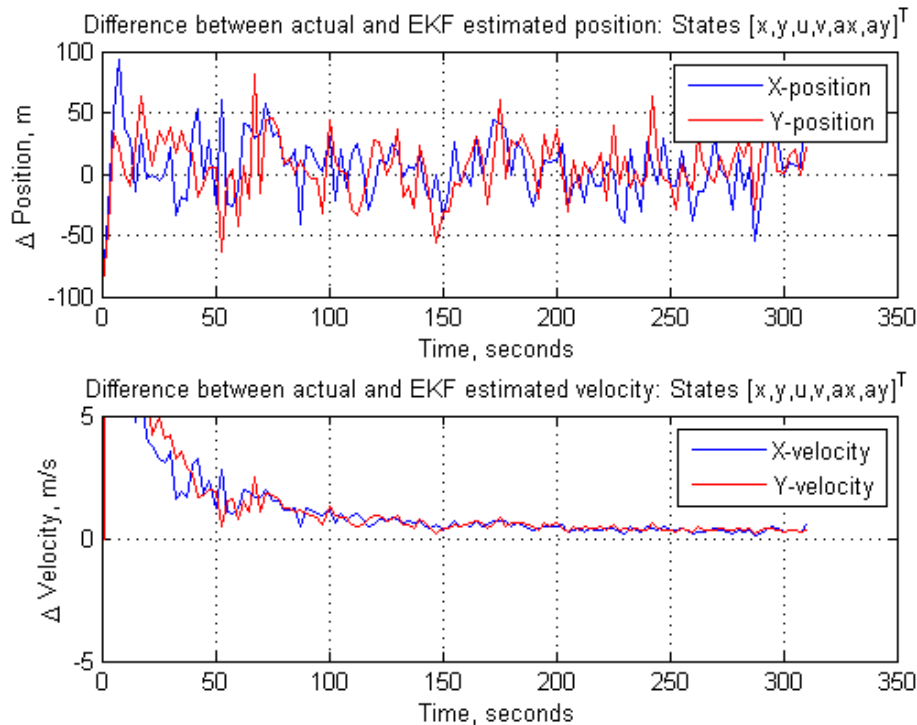


Figure 44: Estimated position and velocity errors.

POC: I. Kaminer (kaminer@nps.edu), V. Dobrokhodov (vndobrok@nps.edu), K. Jones (kdjones@nps.edu)

13. Glider applications in Tactical Oceanography

The Tactical Oceanography (OC4270) course is a capstone course for students in both the Undersea Warfare (USW) and Meteorology & Oceanography (METOC) curricula with a focus on understanding the use of environmental information to enhance mission effectiveness with an emphasis on USW applications. The use of unmanned systems such as gliders to collect critical environmental data in support of operational decision-making is a mainstay of the Oceanographer of the Navy's Battlespace on Demand concept with programs such as Littoral Battlespace Sensing-Glider (LBS-G) bringing these capabilities to reality in the Fleet.

The Tactical Oceanography course includes an at-sea laboratory component through which students collect real-world oceanographic and acoustic data to investigate principles of environmental impacts on system performance. With support from CRUSER, we have recently included the use of the Oceanography Department's "two-man portable" undersea gliders in support of class objectives. In the current OC4270 offering (Summer 2014), a coastal Slocum glider (see Figure 45) was launched on 04-Aug-2014 from the RV FULMAR near the Carmel Canyon wall in southwestern Monterey Bay to assess the environmental conditions in preparation of an acoustics experiment to be conducted 10 days later. The NPS Slocum glider, built by Teledyne Webb Research, is designed to operate in coastal environments. Using

buoyancy control, the Slocum dives to a maximum depth of 200m in a “yo-yo” pattern making repeated measurements of temperature and salinity through the water column for extended periods. The goal of this deployment was to allow students to observe the glider’s performance in a shallow-water environment and to manage the glider’s track over the next two weeks to observe the environmental variability in this area. Unfortunately, the glider detected saltwater on its aft leak sensor and aborted the mission after the first 200m dive. Attempts to redeploy the glider while in the field were unsuccessful and the glider was recovered aboard RV FULMAR. Post-cruise inspection found a few milliliters of saltwater had collected in the science bay and a few drops had trickled back to the aft leak sensor when the glider started its climb to the surface. After consultation with the manufacturer, it is believed the source of the leak was at the O-rings on either end of the science bay. Further testing will be conducted in the upcoming weeks to confirm this. Despite the glider’s mission abort, the students were able to witness the life-cycle of glider operations including preparation of the hardware, mission planning, launch & recovery operations and the bonus of seeing the results of an unexpected operational impairment.

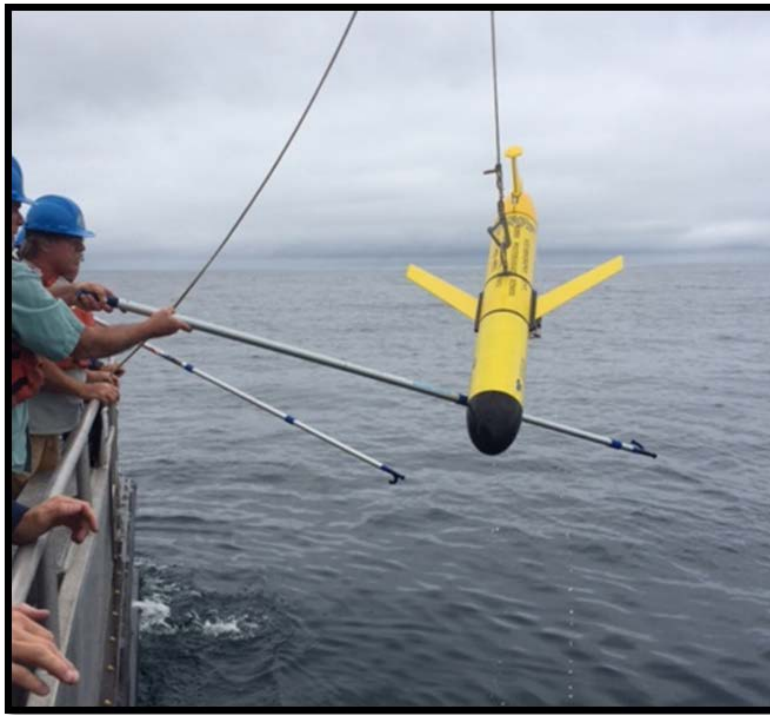


Figure 45. Students aboard RV FULMAR recover the NPS Slocum glider during the Tactical Oceanography at-sea laboratory cruise on 04-Aug-2014

On 12-Aug-2014, a second glider was launched in support of the class field work. This unit was a Spray glider (see Figure 46) developed at the Scripps Institution of Oceanography which is designed for deep-water operations and capable of diving to 1000m. In addition to sensors for temperature and salinity measurements, the NPS Spray had a passive acoustic recorder mounted in its science bay capable of making continuous passive acoustic recordings for a period of 6-7 days. Through collaboration with the Monterey Bay Aquarium Research Institute (MBARI) and

the Scripps Instrument Development Group (IDG), the glider was piloted from Moss Landing to a site over Carmel Canyon where it made a series of dives to 1000m. On each dive, the glider was programmed to remain at 1000m for 1 hour to make acoustic measurements without interfering self-noise from typical flight control adjustments made while the glider dives or climbs through the water column. On 14-Aug-2014, the Tactical Oceanography students returned to sea aboard RV FULMAR to transmit a series of mid-frequency acoustic signals to a variety of distributed receivers, including the receiver aboard the Spray glider.

Students were able to track the progress of the glider and view its science and engineering information in near real time through the publicly available Spray website set up by Scripps IDG (http://spray.ucsd.edu/pub/rel/bin/data_page.php?mission=0034act). Temperature and salinity profiles from the glider were sent directly from the field to the Naval Oceanographic Office (NAVO) as standard encoded KKYY messages for near real time assimilation into the Navy's operational ocean models. By having the data assimilated into the models, the students are able to observe the impacts of data on model output which lays the foundation of operational METOC tactical support. The Spray glider sent over 30 profiles to NAVO during this mission, many as deep as 1000m. The glider was piloted back to its launch site just outside Moss Landing harbor and recovered by NPS and MBARI personnel on 19-Aug-2014.



Figure 46. NPS Spray glider with acoustic receiver deployed near Moss Landing on 12-Aug-2014

The use of gliders has added depth to the course content of the Tactical Oceanography course. Students are gaining hands-on experience with the tools of the future both from an operational perspective and by using the data they collect to conduct analyses for class project presentations on tactical applications of environmental data. With CRUSER support, NPS has been able to establish essential collaborations with MBARI and the Scripps IDG so that NPS personnel are gaining the necessary technical skills to successfully deploy undersea gliders regularly in support

of Tactical Oceanography objectives. We will continue to work these groups to conduct additional Spray deployments in the near future to improve our in-house technical capabilities.

Conducting glider operations with an acoustics spin effectively in Monterey Bay is challenging and requires significant amount of complex choreography. We appreciate the support from our curriculum sponsors who have augmented the class by making key equipment available for use with the gliders (e.g., source and receivers). Monterey Bay National Marine Sanctuary personnel helped us navigate the permit process needed to deploy gliders and we thanks the NOAA National Marine Fisheries Service who reviewed and approved our plan and protocols to safely operate a low-power mid-frequency acoustic source in a marine mammal rich environment.

POC: Professor John E. Joseph (jejoseph@nps.edu)

14. Defense against Swarms: A Key Naval Capability

This work explores the potential for applying newly available numerical methods in optimal control to solve and teach motion planning problems created by the search for targets with motion uncertainty characterized by constant but unknown parameters. These recent developments enable the efficient computation of numerical solutions for search problems with multiple searchers, nonlinear dynamics, and a broad class of objectives. We demonstrate the efficacy of these methods through implementing a multi-agent optimal search problem. We then derive an expansion of the optimal search modeling framework which facilitates the consideration of multi-agent searching problems with more general strategic objectives and utilize this expanded framework to implement an example combat defense scenario. This work will be included in a series of modules to be taught in the Autonomous Systems Curriculum at MAE and other departments.

An area of interest in robotics and autonomous vehicle research is the development of optimal or sub-optimal motion planning given uncertainty. In such situations, autonomous agents are faced with the task of optimizing their behavior under a given performance criterion while taking into consideration environmental or infrastructural features which may have an amount of uncertainty. This problem can arise in many situations, including search and rescue operations, robotic guidance, missile defense, and combat situations. In this work we address the question of modeling and numerically implementing motion planning problems created by the task of optimally searching for a target, given uncertainty in target motion. We focus on the case where target motion is characterized by a set of uncertain parameters. We demonstrate that this gives rise to a class of optimal control problems where the constant but unknown parameter values are incorporated in the cost function. We are furthermore able to flexibly incorporate a larger class of objectives, state and control constraints, and nonlinear searcher and target dynamics. This has created a new potential which can be utilized to address a greater variety of problems. In the first part of this work, we describe a framework for modeling basic search problems, derived in work by Koopman (1956), which was originally developed as part of the antisubmarine warfare efforts of WWII and has been widely utilized in industrial and tactical applications since work by Chudnovsky and Chudnovsky (1988). We elaborate on the mathematical problem this model

creates and the new numerical methods now available for solving this problem. We then utilize these methods to implement a high-dimensional search problem with multiple searchers, nonlinear searcher dynamics, and control constraints. In the second part of the effort, we consider a more 'realistic' motion planning problem, where the act of searching for targets is done in the service of a strategic objective of protecting assets from the targets. This is a goal which can arise in many applications similar to but distinct from search; for instance, during an oil spill a valuable at-risk ecosystem may need to be prioritized during clean up. In these situations, optimization of a basic search objective may be valuable, however as this approach would be indirect it would not necessarily provide an optimization of the primary goal. Direct optimization of the primary strategic goal requires the modeling of additional directions of heterogeneous influences, which is not a feature of current search models. We build a framework for modeling this additional direction of target influence and demonstrate that the new numerical methods can be applied to these scenarios as well. We then use these methods to numerically implement this framework on an example tactical simulation.

Though solutions to search problems have historically been limited to simple cases, the development of more efficient numerical methods has now made complex problems approachable. Due to these developments we are able to use more efficient numerical methods, such as pseudo-spectral collocation, than have been previously implemented. We are furthermore able to flexibly incorporate complicated objectives, state and control constraints, and non-linear searcher and target dynamics. We have demonstrated the effectiveness of this by example through implementing nonlinear multi-agent search problems and presenting their tractability and functionality. These problems are implemented in seconds, rather than hours or days, and demonstrate a potential for these methods to be applied to real-time situations. This latter feature makes it particularly suitable for the classroom environment and will be further explored during the rest of the funding period

POC: Dr. I. Kaminer (kaminer@nps.edu), Dr. V. Dobrokhodov (vndobrok@nps.edu), and Dr. K. Jones (kdjones@nps.edu)

15. NPS-NAVAIR UAS IFC Challenge

The series of Systems Engineering Capstone projects described below was initiated by Dr. Millar's request to NAVAIR 4.1 Systems Engineering for research topics suitable for Capstone projects for the NAVAIR cohorts undertaking the NPS MSSE program. NAVAIR settled readily on an issue of concern for both NAVAIR and NPS: the preparation and approval of Interim Flight Clearances (IFC) for experimental unmanned aviation systems (UAS).

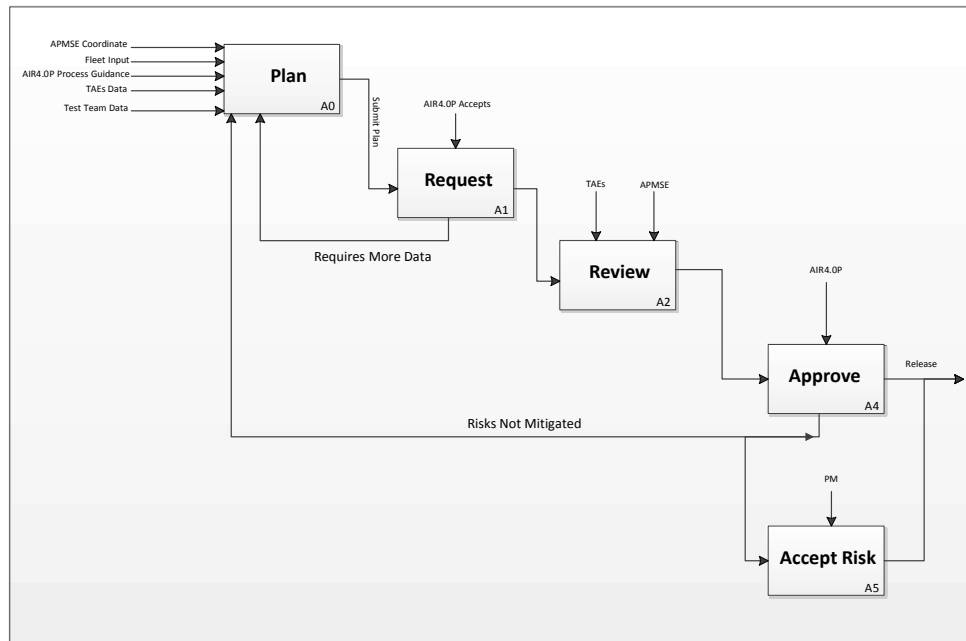


Figure 47. Interim Flight Clearance Process

The rigorous IFC process was defined over many years to assure safety of flight and control of other hazards to developmental flight test, in the context of program of record acquisition and sustainment of US Navy aviation assets. This process is well tuned to this activity, drawing on the massive human resources and facilities available for this purpose, at both the Navy and its industrial base. A key aspect in the IFC process's utility is the Navy's access to the design and other data generated by the suppliers and system integrators under contract in acquisition programs, and the deep knowledge base of NAVAIR engineers.

With the proliferation of experimental flight test of unmanned vehicles, with their novel risks and hazards, the Navy turned to their proven process and mandated that all experimental flight tests also required an approved IFC. This encompasses NPS, NRL and any other Navy organizations and facilities contemplating flight testing of systems or airborne operations.

Immediately, difficulties surfaced in expediting the compilation and preparation of IFC to suit the compressed lead-times, technical data shortfalls and unknowns of experimental flight test. These difficulties impeded NPS research programs, frustrated researchers and the NAVAIR engineers, and busted budgets at both NPS and NAVAIR. NAVAIR suggested that NPS work with them to understand the context and needs of the IFC process, identify and analyze the challenges, and propose and demonstrate solutions.

CRUSER endorsed this challenge and accepted successive proposals covering NPS's incremental costs for the program surveyed below. NAVAIR invested the key resource: the time of their personnel in, actively participating as stakeholders and technical area experts (TAE) throughout, including NAVAIR 4.0P (Airworthiness) as the final judge of a satisfactory IFC process. NAVAIR/MPs MSSE student teams defined & performed the project tasking.

Phase I: NPS/NAVAIR UAS Interim Flight Clearance for ScanEagle (Q4 AY13 – Q2 AY14)

The Phase I team took on the task of scoping and understanding the challenge, using the test case of proposed Scan Eagle trials at NPS and taking a systems engineering approach of modeling the IFC process as implemented for NAVAIR acquisition programs in comparison to NPS experimental flight test. By the end of this nine month project, it evident that the hurdles and bottlenecks for NPS IFC were primarily access to data on COTS & experimental hardware, limited support infrastructure (human & facilities) and communications bottlenecks. A number of useful mitigations are proposed, but simply working the problem as a NPS/NAVAIR team created a common understanding and accommodations that facilitate IFC preparation and release.

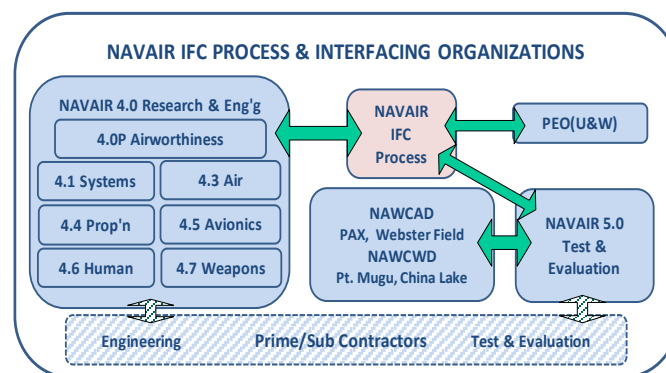


Figure 48. NAVAIR IFC Context

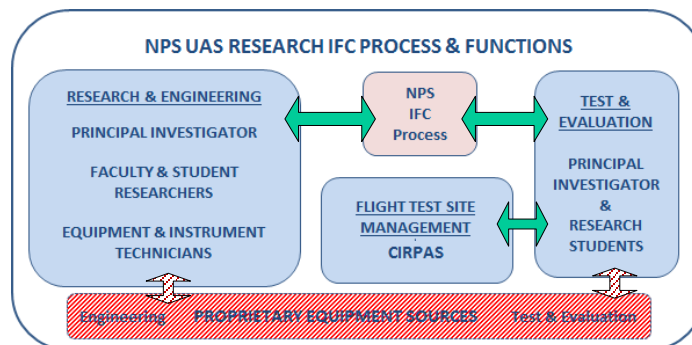


Figure 49. NPS IFC Context

Phase II: NPS/NAVAIR UAS Interim Flight Clearance Phase II (BBN proto) (Q2, AY14 –Q4, AY14)

The second phase kicked off 6 months later, by which time Ph. I had greatly improved the common understanding of the IFC process and necessary accommodations. A key need emerged: a common hazard & risk analysis (HRA) tool that could marshal both “hard” quantitative assessments and “soft” qualitative judgments. It was decided to investigate and pilot the use of Bayesian belief networks (BBN) to enable joint NPS/NAVAIR HRA. Ph. II is

concluding with a positive assessment of BBN utility in eliciting and accommodating expert judgment in capturing the architecture of the influences on system safety, and the probability of adverse outcomes, and recommends further trials with diverse UAS configurations and missions.

Phase III: NPS/NAVAIR UAS Interim Flight Clearance Phase III (OO-BBN Demo)
(Q4, AY14- Q2, AY15)

Phase III has kicked off with the selection of two current applications:

- a) NPS's Rascal UAS ISR trials and
- b) NRL's unmanned Jackal helicopter mission as a platform for over water EW experiments. This phase will demonstrate modular "object oriented" BBN HRA model templates addressing the crucial UAS hazards: collision, crash and containment for both platforms.

The NPS/NAVAIR team is considering the path to transition this jointly developed technology as HRA "standard work" for Navy experimental UAS flight clearance.



Figure 50. NRL Jackal UAS

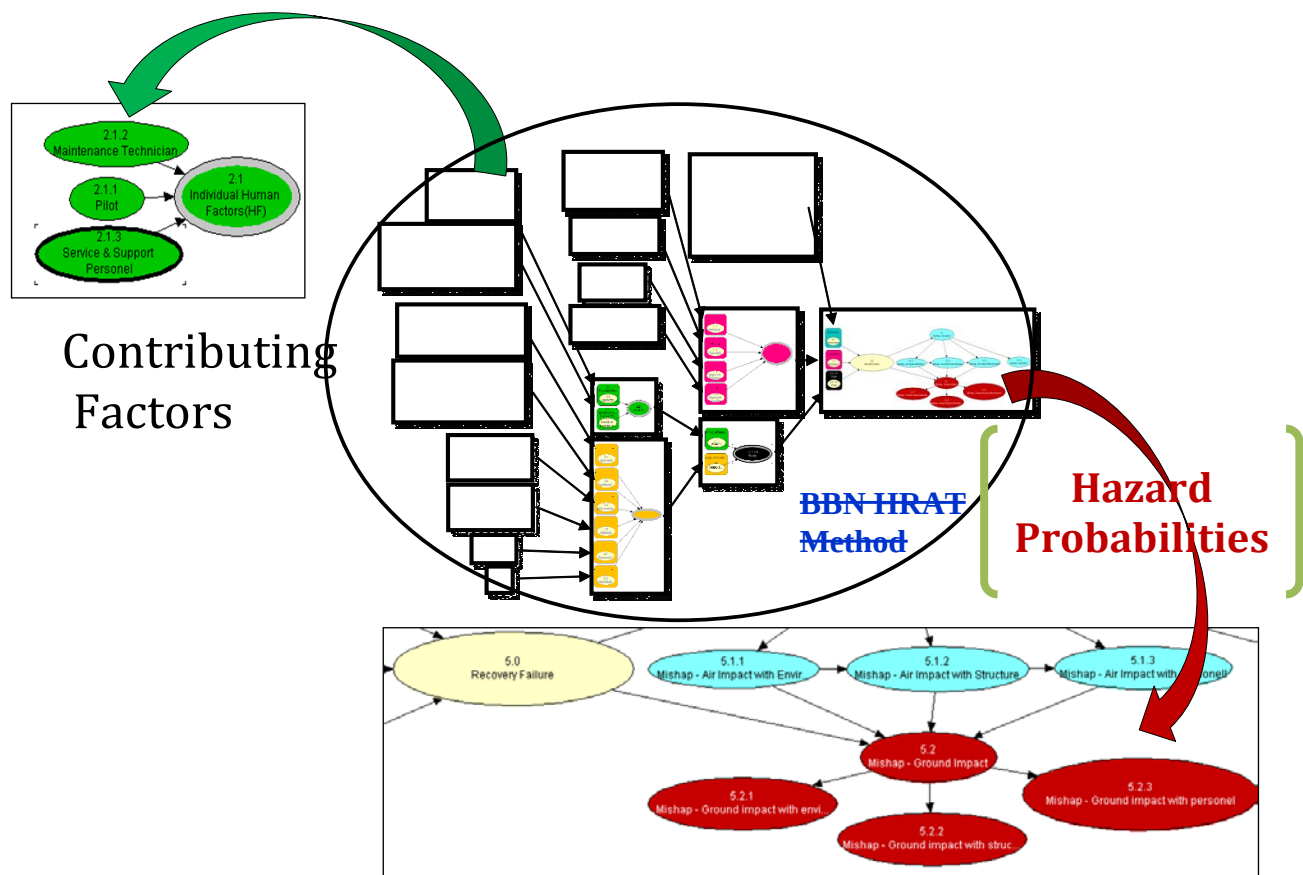


Figure 51. BBN Hazard & Risk Analysis Tool

POC: Dr. Richard C. Millar (rcmillar@nps.edu)

16. Command & Control of Highly Autonomous Systems and People

The objective of this research is to develop command and control (C2) computational modeling and simulation capability, with particular emphasis on teams of autonomous systems and people (TASP) working together coherently in organizations, and to create a suite of research, policy, planning and decision making tools.

Key Findings

Key findings indicate that select mission costs can vary by an order of magnitude across different manned and unmanned aircraft and C2 contexts; that no single C2 approach and organization is best across all C2 contexts; that alternate C2 approaches and organizations are examined best via simulation before attempting them with manned or unmanned systems in the field; that C2

approaches and organizations will likely have to shift from one mission-environment context to another; and that follow-on research is required to understand the implications and guide practice.

Succinct Background and Motivation

The technological capabilities of autonomous systems (AS) continue to accelerate. Although AS are *replacing* people in many skilled mission domains and demanding environmental circumstances, people and machines have complementary capabilities, and *integrated* performance by AS and people *working together* can be superior to that of either AS or people working alone. We refer to this increasingly important phenomenon as **Teams of Autonomous Systems and People (TASP)**, and we identify a plethora of open, C2 research, policy, planning and decision making questions, for which current research methods and contemporary practice are woefully inadequate to address.

Computational modeling and simulation offer unmatched yet largely unexplored potential to address C2 questions along these lines. Computational models can simulate—very quickly and inexpensively—the behavior and performance of hundreds or even thousands of different C2 approaches (e.g., *Deconfliction*, *Coordination*, *Edge*) and TASP mission-environment contexts—including those involving **C2 organizations and AS technologies yet to be developed!** The central problem is, this kind of C2 organization modeling and simulation capability (esp. adapted to and validated for military C2) does not exist at present in the TASP domain.

Approach

The research centers on developing a C2 computational modeling and simulation capability to represent the dynamic structures and behaviors of alternate C2 approaches, AS technologies, and mission-environment contexts. We develop an agent-based model that captures and reflects the structure, behavior and performance characteristics of C2 organizations in the field, and we use it to examine alternate C2 approaches and AS capabilities—both as available today and projected for the future—in the context of exploring TASP opportunities, alternatives and decision spaces.

Working closely with the Commander Third Fleet staff and the Navy Aviation Type Commander staff, we examine extant Navy organizations, ships and AS in terms of aircraft intelligence, surveillance, and reconnaissance (ISR) missions at sea, focusing specifically on the AS onboard ships comprising a representative CTG (Task Group) organization. This can include a carrier (CVN), destroyers (DDG), littoral combat ships (LCS) and other maritime platforms. Each mission is nominally 24 hours in duration, which continues across the various watches, aircraft and crew changes, and like events required for effective, sustained ISR performance.

Table 8 summarizes the six distinct degrees of AS capability that are detailed—ranging from *Degree 0 – no autonomy* (i.e., manned aircraft) to *Degree 5 – future capability* (e.g., AS matching manned capabilities)—including aircraft examples (i.e., F/A-18, SH-60, Scan Eagle, Fire Scout, Triton, future AS).

Table 8. Autonomy Degree Summary

Degree	Capability (and Example)
0	Manned aircraft; continuous human control of flight and sensor operation (F/A-18, SH-60)
1	Remote manual control of flight and sensor operation (Scan Eagle)
2	Preprogrammed flight; remote manual control of sensor operation (Fire Scout)
3	Preprogrammed flight and sensor operation (Triton or Global Hawk)
4	Autonomous decisions and flight and sensor operation (Future capability)
5	Autonomous systems match manned system capability & performance (Future capability)

Four distinct levels of mission interdependence are detailed—ranging from *Pooled* (e.g., manned *or* unmanned missions in separate airspaces) to *Integrated* (e.g., manned *and* unmanned missions in common airspaces). Table 9 outlines these four levels. Probably the most interesting and least understood pertains to *Integrated*: it involves manned and unmanned aircraft flying *together* in common airspaces. For instance, consider the nature of a mission—and its corresponding C2 requirements and complications—with an **unmanned wingman** flying alongside a manned aircraft.

Table 9. Interdependence Level Summary

Interdependence Level	Mission Characteristics
Pooled	Aircraft performing surveillance missions in different geographic areas
Sequential	Surveillance from one aircraft provides targeting information for another
Reciprocal	Two aircraft work together in common airspace
Integrated	Manned and unmanned aircraft work together in common airspace

Together these six degrees of autonomy and four levels of interdependence produce a 24 cell matrix of TASP contexts to be assessed in terms of C2 organization performance. Each cell is represented by a separate computational model, which is simulated 50 times, across 10 performance dimensions (e.g., cost, coordination, mission risk), to create a substantial performance space for analysis.

In this present study, we examine each of these 24 test cases in terms of *extant* C2 organizations and approaches. In follow-on work, we can examine each of these cases in terms of the *best* C2 organizations and approaches. Clearly **no single C2 approach and organization is best in all circumstances.**

The computational modeling and simulation environment is called POWER, which derives from over two decades of research at Stanford and nearly one decade at the Naval Postgraduate School. POWER represents the state of the art in terms of modeling the structures and behaviors of C2 and other organizations. It has been validated dozens of times and demonstrated to emulate faithfully the key structures and behaviors of many different organizations in the field.

Results

Preliminary results are both positive and promising. Figure 52 delineates a screenshot of our baseline CTG organization and platform set. The light (green) person icons represent organizations at four levels (i.e., CTF, CTG, Platform, Aircraft Operators). The dark (brown) rectangle icons represent common tasks (e.g., planning, maintenance, air traffic control), whereas the light (yellow) rectangle icons represent the aircraft ISR mission tasks. Organizations and tasks are represented at appropriate levels: sufficiently low to capture the important structural and behavioral dynamics, but sufficiently high to abstract away details that do not impact the results in terms of TASP C2.

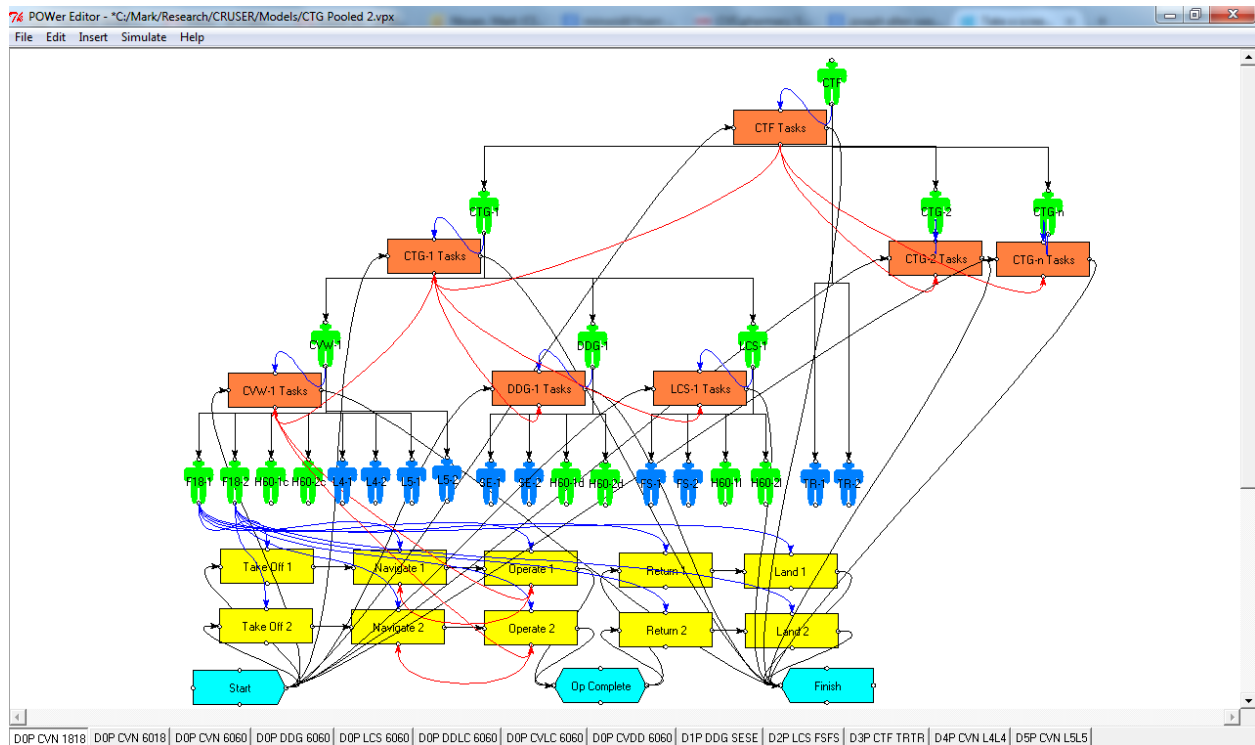


Figure 52 Baseline Model (D0P)

At the lowest level in the organization lies an array of diverse manned (light/green) and unmanned (dark/blue) aircraft. F/A-18s (Degree 0) are assigned to the CVN. SH-60s (Degree 0) are assigned to one or more DDGs and LCSs as well as the CVN. The Scan Eagles (Degree 1) are assigned to the DDGs, and the Fire Scouts (Degree 2) are assigned to the LCSs. The Tritons (Degree 3) are examined as an asset from beyond the CTG itself (e.g., controlled by the CTF), and we examine the two future AS (Degree 4 & 5) in terms of CVN assignment here. The many lines linking various icons in the figure are used to symbolize organization hierarchy, job assignment, task precedence, communication and other important model relations.

In the baseline screenshot above, two (manned) F/A-18s are assigned to fly ISR missions in separate airspaces (i.e., D0P: Degree 0 Autonomy, Pooled Interdependence). Here both (manned) aircraft are assigned to the same (CVN) platform and (CVW) organization, and each flies in a different region of airspace. This represents a very common and relatively straightforward C2 context.

Not surprisingly the simulated operating cost and other performance aspects of conducting *the same 24 hour ISR mission* vary considerably across platforms. The F/A-18s, for instance, represent the most costly ISR platform, but they also exhibit the greatest speed and mission flexibility (e.g., attack). The SH-60s cost roughly half as much, are comparable to the Fire Scouts, and have distinct capabilities (e.g., rescue operations). Tritons cost about half again as little, and Scan Eagles—along with the Degree 4 and 5 UAVs—cost much less to operate.

A different computational model is developed and employed to represent and examine the other 23 TASP contexts from our matrix above. For instance, Figure 53 delineates a screenshot of a model with Degree 4 autonomy and Integrated interdependence (i.e., D4I). Notice that one (manned) SH-60 leader from the DDG is supported by and flying together with one (unmanned) L4 UAV (i.e., Autonomy Degree 4 – future capability) from the CVN.

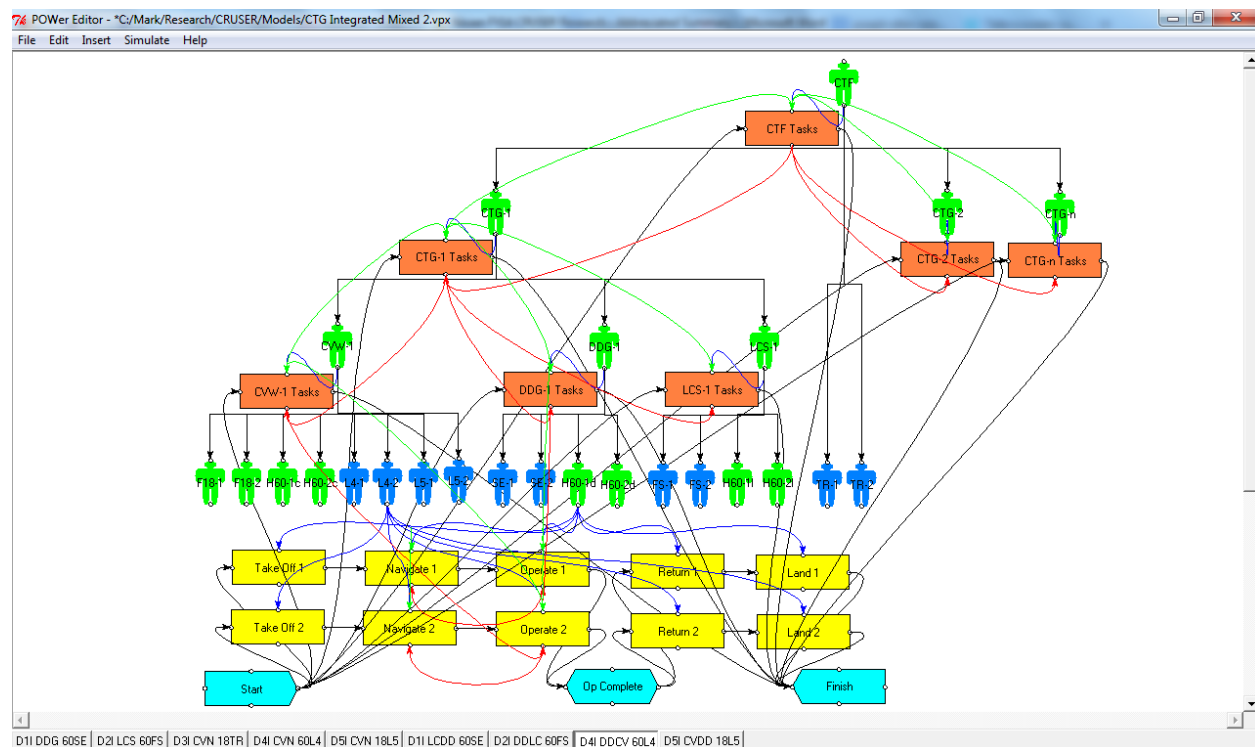


Figure 53 Integrated Model (D4I)

This represents a much less common (if it has occurred to date at all) or understandable C2 context. Indeed, the (manned) SH-60 is assigned to one ship and organization, whereas the (unmanned) L4 UAV is assigned to another, yet *collective and simultaneous C2 are required*. Here the CTG represents the lowest level with authority over both ships and aircraft. This suggests that the current C2 approach and organization are likely to experience significant performance difficulties, a suggestion confirmed by our quantitative results.

Moreover, one or more of the alternate C2 approaches and organizations (e.g., *Collaboration*) to be examined through our follow-on research offers good potential to mitigate such difficulties. This elucidates an organization challenge for the CTG: mission efficacy may require shifting from one C2 approach and organization to another depending upon the TASP C2 context; that is, the same CTG may need to employ different C2 approaches and organizations across the range of diverse TASP contexts, even within the same ISR mission set. Our campaign of computational models and simulations will serve to outline which one is best for each context and how to shift from one to another.

POC: Professor Mark Nissen (mnissen@nps.edu)

17. Real-time undersea networking using acoustic communications for improved AUV positioning and collaboration

The objective of this work was to successfully develop methods for the enhancement of the navigational and positioning accuracy of autonomous underwater vehicles through a combination of autonomous surface vehicles and bottom deployed underwater acoustic seafloor positioning systems using acoustic communications protocols. By comparing the performance of each approach separately and in combination, a more thorough understanding of the versatility of such systems can be obtained.

Approach

The NPS Physics Department's Undersea Sensing System Laboratory (USS Lab) manages a small fleet of UUVs (6 Littoral Gliders originally developed by Alaska Native Technologies) capable of 15+ days of continuous operation. In addition, the USS Lab manages 2 USVs (Wave Glider SV2 systems developed by Liquid Robotics) capable of long-term continuous operation. Previous work undertaken by the NPS Seaweb program utilized a Wave Glider SV2 system with an integrated underwater acoustic modem for communication with acoustic nodes moored to the seafloor. Both systems have been utilized in at-sea testing previously, as shown in Figure 1.

In this effort, new acoustic modems would be acquired and integrated onto the UUV Littoral Glider platforms, allowing them to communicate while submerged with the USV Wave Glider. The modems will be interfaced with a new on-board science computer, which has the ability to interface with other sensors and the glider's command-and-control system. Similarly, an acoustic modem will be integrated onto a USV Wave Glider, and be capable of interfacing with the GPS data on-board. The modems have the capability to establish a two-way link, including a recording of transmit time delays, thereby providing time-of-flight (range) to each system. By transferring the Wave Glider's GPS data, the Littoral Glider can improve its own position estimation while submerged.

Additional software would then be developed and integrated onto the UUV platforms that would accept this additional data and use it for improved location estimation during submerged operations. A Kalman filtering approach to incorporate this additional data into the navigation algorithm is expected to provide the optimal response when only a single USV platform is available. With two USV Wave Gliders deployed simultaneously and providing unique range estimates, the glider's position can be triangulated for even better position estimation. And if similar data links are established between multiple submerged Littoral Gliders, the overall system accuracy can be further improved. The USV Wave Glider would also act as a communications gateway buoy, allowing for remote command and control, remote tracking, and providing a means for data exfiltration.

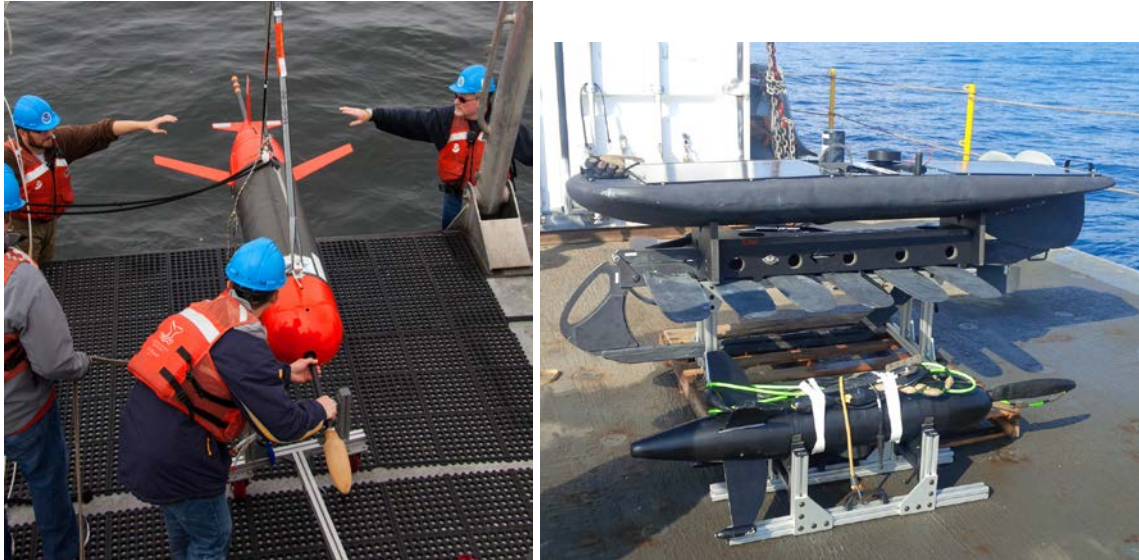


Figure 54. An NPS Littoral Glider UUV rigged with narwhal mount for acoustic sensor being deployed in Monterey Bay (*left panel*); an SSC-SD Wave Glider USV with integrated towed acoustic modem being deployed in Hawaii (*right panel*).

Work Completed

Much of the FY14 work was delayed due to funds availability and contracting issues at NPS. Components for the new PC104-based science computer were obtained in March, 2014. The Teledyne-Benthos modem that will be integrated into the UUV was not obtained until June, 2014. The Wave Glider USV with the integrated towed acoustic modem is not expected to arrive at NPS until September, 2014. A contract for systems engineers to develop much of the embedded software integration was submitted in February, 2014, but was only recently awarded for a start date of August 1, 2014. Still, all of the components are finally falling into place, and an initial at-sea test is expected to occur around November-December, 2014.

The foundations of the science computer have been completed, and the networking between the UUV system and the science computer is now operational. Access to the science computer can be achieved through the existing UUV network, currently accessible via WiFi, Freewave, and Iridium. The direct networking of the science computer and glider computer will also allow direct connection to the glider's computer through the acoustic modem, which will be managed by the science computer.

The modems acquired for this effort, Teledyne-Benthos ATM-903 series, require special bulkhead cabling to incorporate into the UUV platform. This cable was designed and procured in July, 2014. In addition, the weight of the modem (approx. 5 lbs.) will interfere with the UUV operations unless it is countered. For that purpose, blocks of syntactic foam were acquired and designs for a mount that would produce a neutrally buoyant integrated modem package are currently being developed.

The integration of the modem is anticipated to be complete by the end of September, 2014. Software integration and laboratory testing will then occur in October, 2014, before at-sea deployments at the end of the year. Figure 55 shows the new science computer and modem.

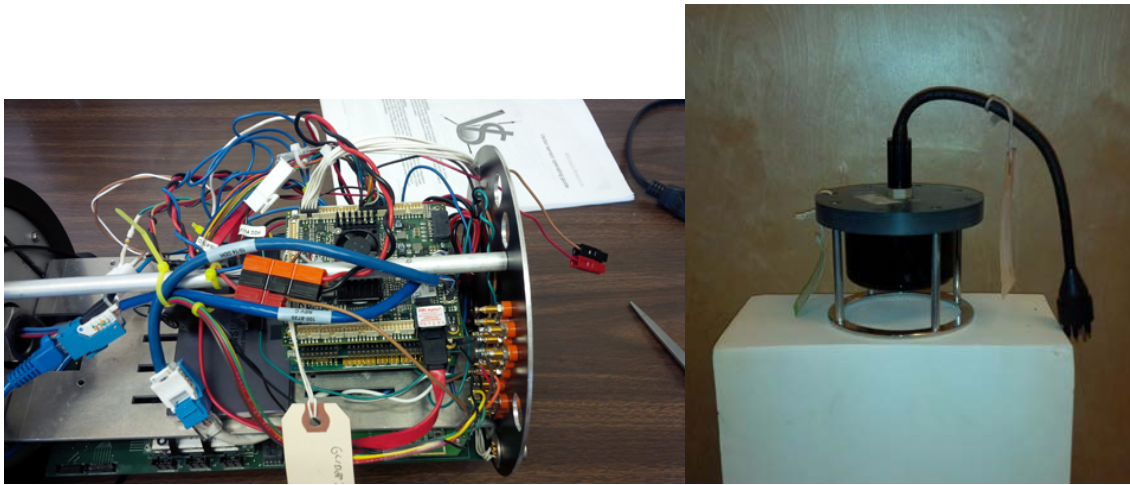


Figure 55. New science computer for Littoral Glider UUV integrated into electronics bay (left panel); Teledyne-Benthos ATM-903 modem with bulkhead connector sitting atop a block of syntactic foam (right panel).

Impact/Applications

The development of a group of reliable, autonomous, integrated platforms capable of persistent submerged monitoring while maintaining accurate position information can be used in a variety of applications in the Navy. Such uses include ad hoc ranges for naval exercises, clandestine surveillance in operational areas, and environmental and marine mammal monitoring. The results from studies with these platforms could impact future DNS architectures.

Related Projects

SPAWAR Systems Center, San Diego has an on-going project, Deep Seaweb, which utilizes nearly identical Wave Glider USV systems as communications gateway buoys. NPS is collaborating with engineers at SSC-SD in order to obtain lessons learned, and capitalize on system improvements they have made over the course of their project.



POC: Dr. Kevin B. Smith (kbsmith@nps.edu)

18. Environmental Data Collection Using Autonomous Wave Gliders

The long-term goal of this project is to maximize the use of the SHARC (Sensor Hosting Autonomous Remote Craft) Wave Glider as a measurement platform for air-sea interaction research and related applications such as electromagnetic wave propagation.

Objectives

The objectives of this project include: 1) Evaluate the adequacy of Wave Glider as a sea-going platform for measurements of the atmospheric and oceanic parameters in quantifying the near surface environment; 2) Integration of research-grade meteorological sensors onto the NPS Wave Gliders; and 3) Engage NPS METOC students in leading edge research on capability and technology development as a crucial component of their education at NPS.

Background

The Wave Glider, built and introduced by Sunnyvale, Calif.-based Liquid Robotics in 2008, is an autonomous ocean vehicle designed as a sea-going platform to support multidisciplinary research and particularly naval applications. It is an ocean wave-propelled unmanned surface vehicle (USV) with a two-body design. The lower ‘glider’ portion of the vehicle is tethered approximately seven meters below the upper ‘float’ portion of the vehicle via an umbilical. The float and glider work in tandem to propel the vehicle through the water using energy harvested from wave action in the ocean.

One of the most attractive features of the SHARC is its capability to deploy different payloads based on mission objectives. The basic meteorology and oceanography (METOC) package on SHARC gathers wind speed and direction, temperature, and barometric pressure together with ocean current data. The METOC Plus model adds a Datawell MOSE-G and Sea-Bird GPCTD to expand its METOC payload. The Datawell MOSE-G GPS-based directional measures 2-dimensional wave spectra that yields wave height, propagation direction, period and the Sea-Bird GPCTD measures water temperature and salinity and can be mounted either on the float or glider portions of the SHARC. Most LRI gliders acquired by Navy laboratories and centers (e.g., NAVO and SPAWAR) for meteorology and oceanography applications are METOC Plus models.

NPS introduced two LRI Wave Gliders its research community in January 2012. The gliders, “Mako” and “Tiburon”, are currently managed by the SeaWeb and Wave Glider Laboratory of the Physics Department. Glider Mako is already equipped with a weather station, the Airmar PB200 Weather Station, for near-surface meteorological measurements. In FY2014, Wave Glider Mako was made available to NPS researchers for sensor development and testing.

Liquid Robotics (LRI) Wave Gliders have great potential as platforms for air-sea interaction measurements for important applications such as radar wave ducting and development and

validation of coupled air-ocean forecast models. Using this platform can enhance air-ocean databases for future basic and applied research aimed at improving environmental forecasts at all time-scales from turbulence to climate. This autonomous surface vehicle is advantageous because it is mobile and relatively easy to deploy, and is designed to be continuously powered for sensor operation. Development of a robust METOC sensing system on the Wave Glider is crucial for those applications. However, the simple METOC system, (Airmar PB200) currently on most of the SHARCs, has not been thoroughly evaluated.

Approach

Our work within this project consists of instrument development, at-sea testing of new sensor packages, and subsequent data analysis. We have done extensive laboratory testing to develop a METOC sensor and data acquisition system for the SHARC. The new system was deployed with the Airmar PB200 simultaneously, and the NPS Mini Air-Sea Flux buoy (MASFlux) nearby. Data sets from the three sensor systems/platforms will be compared to evaluate the performance of the Airmar PB200 system and the new NPS SHARC METOC mast.

NPS personnel involved in this project includes Qing Wang (PI) and Kevin Smith (Co-PI), Dick Lind (sensor development), and Ryan Yamaguchi (NPS contractor, sensor development and Wave Glider deployment). NPS student, LCDR Kate Hermsdorfer, is involved from multiple angles and is working on the data analyses as part of her thesis work. All have been actively involved in the at-sea deployment of the SHARC.

Work Completed

Our work in FY14 includes:

1. Design and integration of a new METOC sensing system as an environmental sensing package for the SHARC.
2. At-sea testing of the SHARC with the new SHARC sensor package together with co-located MASFlux. Three at-sea deployments were made for testing the new sensor package.
3. Initial analyses of the datasets collected for sensor evaluation purposes.

Results

New METOC sensing package Developed for Wave Gliders: Under FY14 CRUSER funding, we have designed and integrated a new METOC sensor package specifically for the LRI SHARC. The system, mounted on the NPS SHARC, Mako, is shown in Figure 1. This system provides wind speed and direction, air temperature, humidity, pressure, and water temperature. Wave Glider motion was sampled using a combination of GPS, compass, and accelerometer, from which platform motion can be removed from direct wind measurements and surface wave information can be derived from platform motion. The mast is about 1 m high above the water line and is mounted aft. The data acquisition system is sealed in a water-tight box and tucked into the aft bay of the SHARC. The front bay of the glider hosts extra batteries for extended hours of

measurements. Power from the solar panel is also used, in addition to the battery pack stored onboard. Data were stored locally on the SHARC and were downloaded to portable media at the end of each deployment.

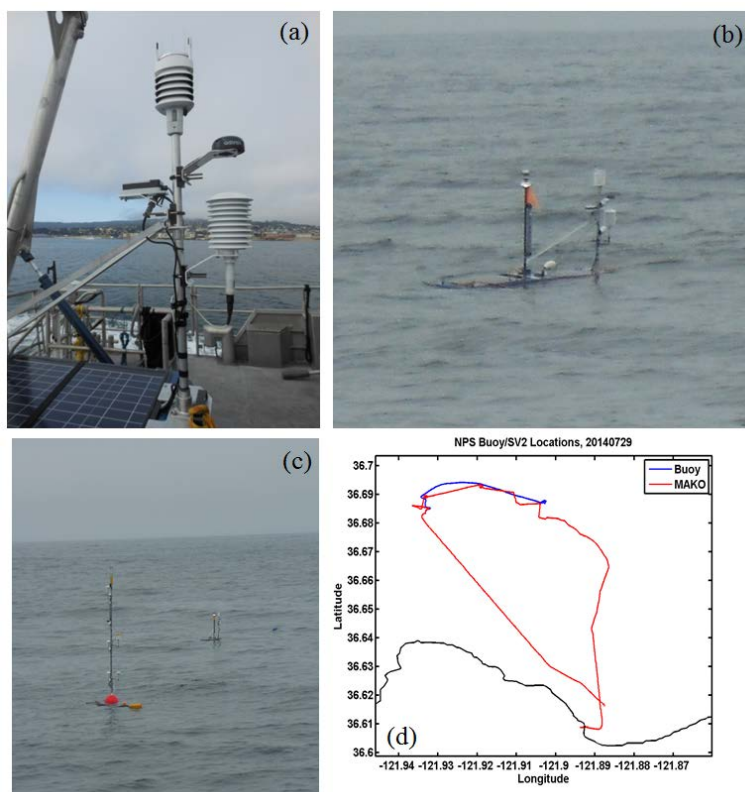


Figure 56. (a) New METOC sensor mast mounted on NPS Wave Glider Mako. Mako was sitting on the deck of R/V Fulmar before the field deployment on July 30, 2014; (b) Mako deployed in Monterey Bay with the Airmar mast (with an orange flag) and the new NPS METOC mast

Wave Glider at-sea testing: Three successful at-sea testing were made on board the NOAA R/V Fulmar on July 29, 30, and August 8, 2014. During each cruise, the MASFlux buoy and SHARC Mako were deployed in close proximity to ensure that the two platforms sampled the same air/water mass. The measurement periods from each deployment were about 5 hours on each day. All three days were in relatively calm conditions with slightly stronger wind towards the afternoon hours. Weak wave/swell fields were encountered on the first two days, while significant swell conditions were observed on August 8.

Deploying/recovering SHARC with two sensor masts (the Airmar and the new mast) was quite a challenge to ensure that the sensors on the masts were not damaged. We developed a procedure for this process to keep the SHARC level and stable, particularly during recovery. This procedure was proved a success during the recovery of the SHARC on Aug 8, 2014 in high seas of strong swell.

Preliminary Data Analyses: The three testing cruise trips yielded a significant amount of data for future detailed analyses, which will be part of LCDR Kate Hemsdorfer's thesis work. Initial

analyses suggest that most sensors were working as expected, except for the water temperature measurements from the thermistor mounted below the glider body showing little SST variation. Two independent water temperature probes were added to Mako on the Aug 8 deployment to help diagnose possible reasons. Figure 57 shows a comparison of wind speed measured from three sets of probes from different platforms. The SV-2 Airmar PB200 measurements were averaged at 10 minute intervals and transmitted to researchers through the internet. Although the Airmar sonic anemometer wind speed is not capable of revealing small scale wind variability, it appears to be able to represent the general trend of variation. The adequacy of such measurements for METOC application needs to be further accessed. Agreement can be seen between the wind speed from the new METOC package on the SHARC and that of the NPS MASFlux buoy. Overall, the new METOC sensing package shows reliable measurements in comparison to the buoy data.

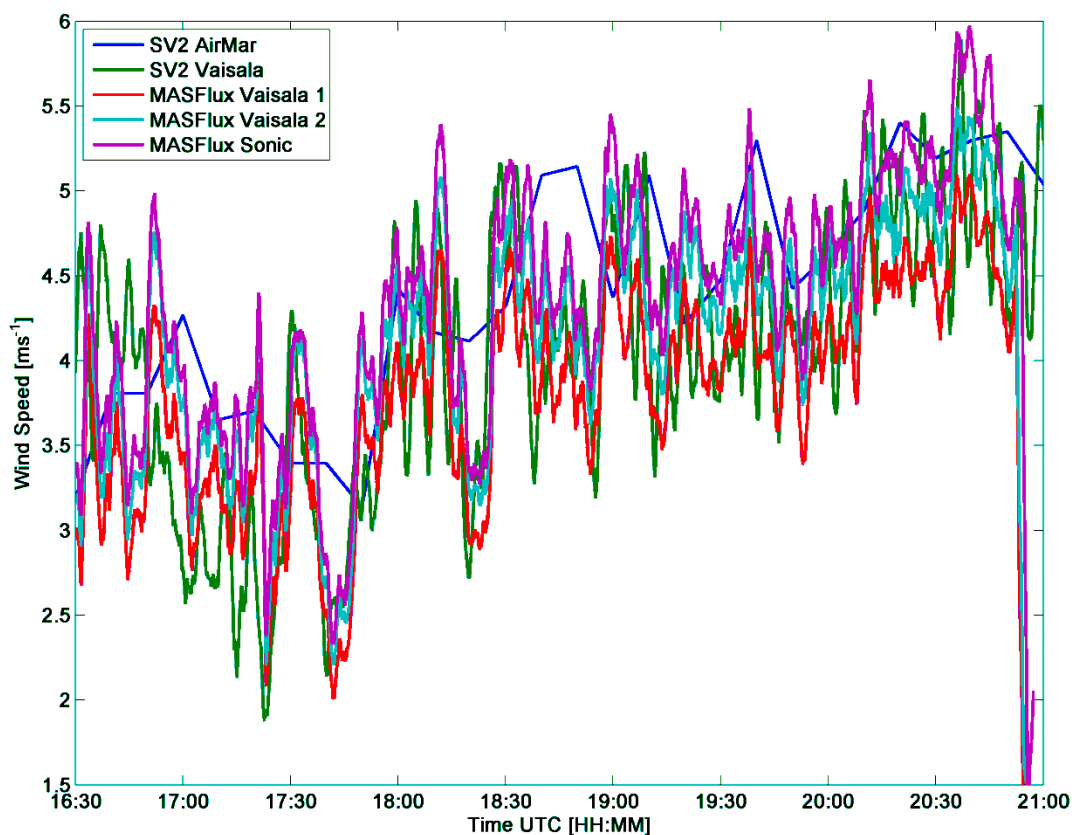


Figure 57. Intercomparison of wind speed from the WG original sensor (blue), new METOC sensor package, and the MASFlux nearby.

POC: Dr. Qing Wang (qwang@nps.edu) and Kevin Smith (kbsmith@nps.edu)

C. CONCEPT GENERATION

The first NPS Innovation Seminar supported the CNO sponsored *Leveraging the Undersea Environment* war game in February 2009. Since that time, warfare innovation workshops have been requested by various sponsors to address self-propelled semi-submersibles, maritime irregular challenges, undersea weapons concepts and general unmanned concept generation. Participants in these workshops include junior officers from NPS and the fleet, early career engineers from Navy laboratories, academic and industry partners, and NWC Strategic Studies Group (SSG) Director Fellows.

1. Warfare Innovation Workshops

The first CRUSER sponsored Warfare Innovation Workshop (WIW) was in March 2011, shortly after the formal launch of the Consortium. Since that time CRUSER has sponsored six complete workshops covering topics of interest to a wide variety of the full community of interest. Workshops to date include:

- 1) Future Unmanned Naval Systems (FUNS) Wargame Competition, March 2011
- 2) Revolutionary Concept Generation from Evolutionary UxS Technology Changes, September 2011
- 3) Advancing the Design of Undersea Warfare, September 2012
- 4) Undersea Superiority 2050, March 2013
- 5) Distributed Air and Surface Force Capabilities, September 2013
- 6) Warfighting in the Contested Littorals, September 2014

Our most recent workshop, Warfighting in the Contested Littorals, was held 22-25 September 2014 on the NPS campus. This NWDC and CRUSER sponsored workshop included over 70 participants representing a wide variety of stakeholder groups.

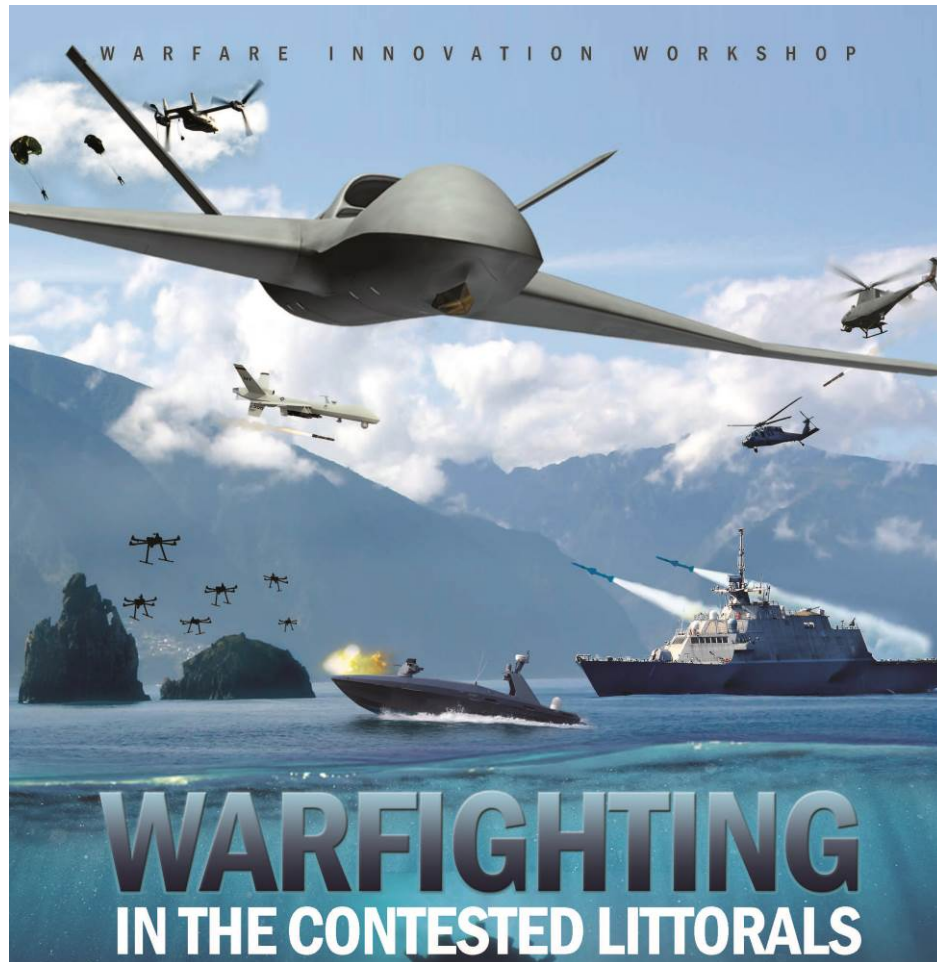


Figure 58. September 2014 Warfare Innovation Workshop, "Warfighting in the Contested Littorals"

Emerging technologies in unmanned systems; autonomy; missile systems; undersea systems; long-range, netted and multi-domain sensors; and networks create a new environment for operations on and over the sea. This changing technology environment both challenges traditional fleet operations and creates opportunities for innovative tactics, techniques, and procedures to achieve naval objectives in sea control, power projection and counter Anti-Access Area Denial (A2AD) strategies in the littorals. This workshop focused on warfighting in the complex and electromagnetically contested environment of the littoral. It addressed opportunities in swarm ISR to support tactically offensive operations, expeditionary mining and marine raid concepts, alternative methods of ship to ship communications in a Network Optional Warfare concept, laser weapons in defense, and other related research topics. The larger research question was "Will emergent technologies (unmanned systems, advanced computing power, automation, advanced sensor capabilities, laser weapons etc.) allow us to fight effectively in the complex and electromagnetically contested littoral environment against sea denial forces?"



Figure 59. September 2014 Warfare Innovation Workshop participants

As with past workshops, participants (*see Figure 59*) included NPS students from across campus, as well as guests from Navy labs, other DoD commands, academia and industry. After a morning knowledge-leveling plenary briefings, team participated in an innovation seminar by Dr. Neal Thornberry, NPS Innovation Initiatives Lead. Teams spent the next two days generating concepts to enhance future warfighting in the littoral environment, and presented their chosen concepts on Thursday morning. All participants earned Continuing Education Credits (CEUs) from the Naval Postgraduate School for this event. CEUs will be awarded as part of CRUSER's education mandate for any CRUSER activity that meets applicable academic guidelines.

In the first few weeks of FY15 CRUSER leadership will review all the proposed concepts to select ideas with potential operational merit that aligned with available resources. Selected concepts will begin CRUSER's fourth Innovation Thread, and members of the CRUSER community of interest will be invited to further develop these concepts in response to the FY15 Call for Proposals. A final report detailing process and outcomes will be released before the end of 2014 to a vetted distribution list of leadership and community of interest members. Technical members of the CRUSER community of interest will make proposals to test concepts in lab or field environments.

2. CRUSER Technology Continuum (TechCon), April 2014



Figure 60. CRUSER Technical Continuum (TechCon), April 2014

NPS CRUSER held its third annual Technical Continuum (TechCon) on 8 and 9 April 2014 (see Figure 60). This event was for NPS students and faculty interested in education, experimentation and research related to employing unmanned systems in operational environments.

Table 10. CRUSER Technical Continuum presentations, April 2014 (alphabetical by speaker name)

TOPIC	SPEAKER
<i>Unmanned Systems Network for Supporting the Vessel Boarding Operations</i>	Dr. Alex Bordetsky
<i>Galerkin Optimal Control for Constrained Nonlinear Problems</i>	LTC Randy Boucher, USN

<i>Optical Signaling for QR-Code Data Streaming and Digital Flashing Light (DFL), in support of Network Optional Warfare (NOW)</i>	Dr. Don Brutzman
<i>Afloat Research Operations using Wave Glider SV-2 Unmanned Surface Vehicles (USVs)</i>	Dr. Don Brutzman
<i>Energy Independent UAV Cloud in Support of Remote Naval Operations</i>	LT Nahum Camacho, Mexican Navy
<i>Swarm Flock Formation and Human Interaction</i>	LT Brenton Campbell, USN
<i>Advanced Concepts and Field Experimentation of Large-Scale Swarm Aerial Robot Systems</i>	Dr. Timothy Chung
<i>Guidance of Proximity Maneuvers by Dynamics Inversion and Sequential Gradient-Restoration Algorithm</i>	Dr. Marco Ciarcia
<i>A Mathematically Rigorous Command and Control Paradigm Supporting Ethical Autonomous Vehicle Mission Execution</i>	Dr. Duane Davis
<i>Energy Independent UAV Cloud in Support of Remote Naval Operations</i>	LT Chase Dillard, USN
<i>Tools for the 2050: Exploration in Extreme Environments</i>	Dr. Noel Du Toit
<i>Investigating the Navy's Role in Humanitarian Assistance</i>	LCDR Maxine Gardner, USN
<i>Atmospheric Measurements from a Mini-Quad Rotor UAV – How Accurate are Measurements Near the Surface?</i>	Dr. Peter Guest
<i>SEA VEX and East China Sea Future Conflict</i>	Maj Adam Haupt, USA
<i>Wireless Power Transmission for Battery Charging Applications</i>	Dr. David Jenn
<i>Robotic Outposts to Support Persistent AUV Operations</i>	Mr. Sean Kragelund
<i>The Future Naval Air Wing</i>	LCDR Vincent J. Naccarato, USN
<i>NPS Spacecraft Robotics Lab (2004-2014)</i>	Dr. Marcello Romano
<i>CRUSER Data Farming Workshops: Better Insights by Design</i>	Dr. Susan M. Sanchez
<i>Exploring the Use of Wide Area Decoy UAS Swarms Against Integrated Anti-Air Defense Systems</i>	Capt Caroline A. Scudder, USMC
<i>Evaluating the Combined UUV Efforts in a Large-Scale Mine Warfare Environment</i>	LT Andrew Thompson, USN

<i>An Adaptive Control Approach for Precise Underwater Vehicle Control for Combined Robot-Diver Operations</i>	LT Nicholas Valladarez, USN
<i>Theory and Laboratory Model of a Robotic Vehicle with an On-Board Manipulator</i>	Dr. Markus Wilde

TechCon 2014 was intended to further concepts developed during the September 2013 Warfare Innovation Workshop, and showcase NPS student and faculty work in advancing undersea operations capabilities. Concepts presented at the September 2013 Warfare Innovation Workshop were coalesced into three broad focus areas that include a host of specific research questions. These areas were:

- 1) **Asset Distribution and Employment Concepts:** surface flotilla with expeditionary basing and optionally-manned ships, subsurface flotilla with semi-submersible platforms, distributed expeditionary airbases, dissimilar swarm autonomy, autonomous coordinated UxS maneuvers for sensor positioning, and UAV payloads to augment strike capabilities
- 2) **C2/3 Concepts:** wave-gliders for cueing and C3 networks, virtual crow's nest, full network deployment, leverage ambient signals, C2 for hunter-killer mindset, UAV "Carrier Pigeon," UxS C2 modification, strategic UxS C2, force allocation and employment, biologically encoded acoustic communication , IR "Bat Signal," innovative C3 systems for distributed manned and unmanned platforms and systems
- 3) **Deception and Weather Concepts:** sea chaff or sea flare, disruptive swarm, weather weapons

TechCon 2014 was held in a tent out on the academic quad. Presentations covered on-going student and faculty research, as well as proposals for CRUSER FY15 funding in research related to unmanned systems. The NPS CRUSER TechCon 2014 was unclassified.

D. OUTREACH AND RELATIONSHIPS

CRUSER continued to grow its membership throughout 2014. In the two years spanning 2012-2014 CRUSER has doubled in size, from just of 800 members in September 2012 to approximately 1630 members as of September 2014. This is largely due to CRUSER web presence and member interaction with military, academic and industry personnel during field experimentation, workshops, educational for and CRUSER monthly meetings. Figure 63 graphic depicts this continued steady rise in CRUSER membership.

1. Community of Interest

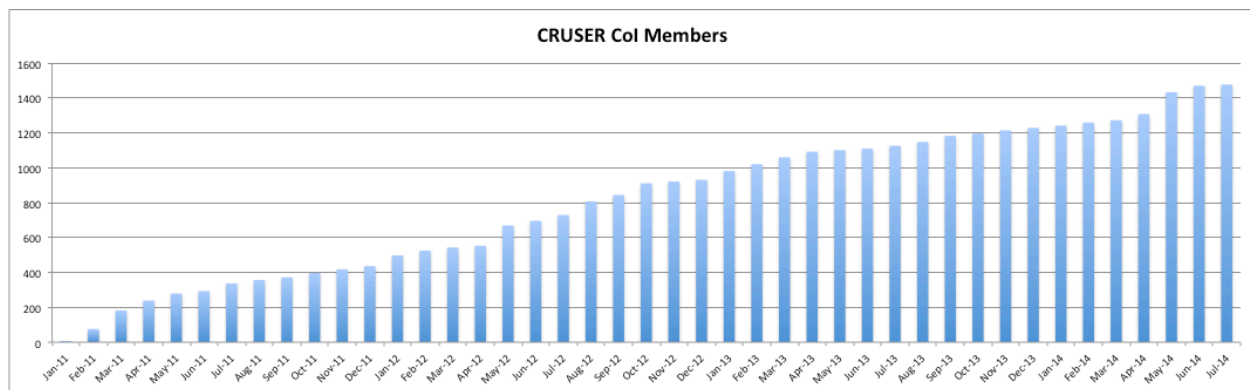


Figure 61. CRUSER community of interest growth from January 2011 to July 2014

At the end of FY11, CRUSER’s first program year, the CRUSER community of interest had grown to include almost 400 members. As of March 2014 this fledgling community consisted of over 1,300 members (*see Figure 61*). Beyond NPS community members, the CRUSER community of interest includes major stakeholders from across the DoD, as well as significant representation from industry and academia (*see Figure 62*).

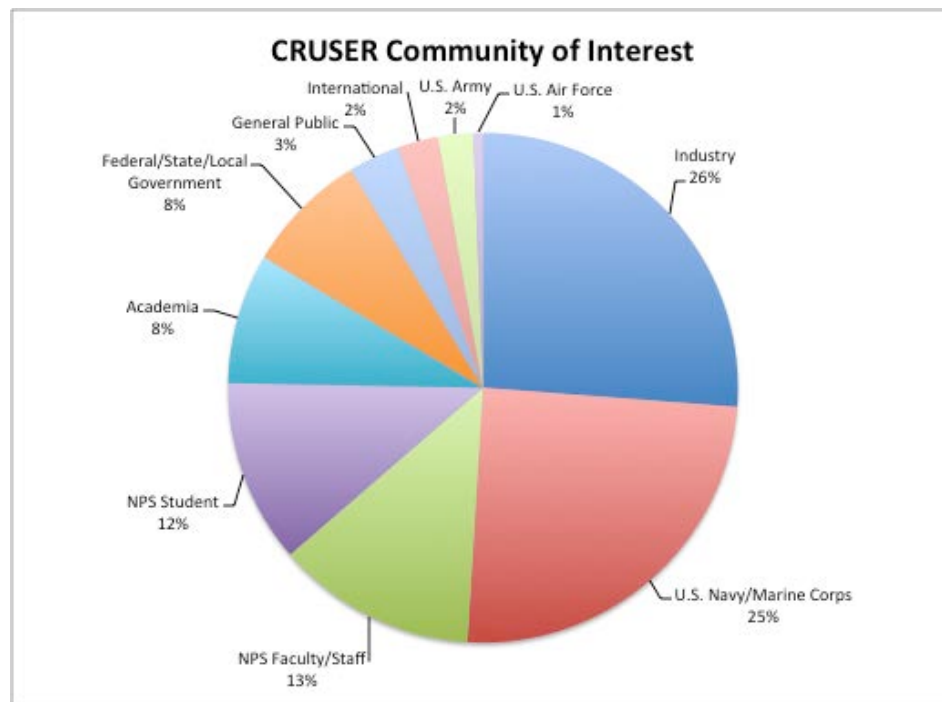


Figure 62. CRUSER community of interest breadth of membership, July 2014

CRUSER continues to produce a monthly newsletter, and accepts article submissions from the entire community. This four-page document is sent electronically each month to the entire

community distribution list, and just distributed Issue 43 on 16 September 2014. Additionally, CRUSER holds a monthly community meeting on the NPS campus (see Figure 63).



Figure 63. CRUSER monthly meeting in progress, September 2013

Non-resident members may join the meeting by phone, video, or using the campus distance learning tool Collaborate.

2. 4th Annual Robots in the Roses Research Fair, April 2014

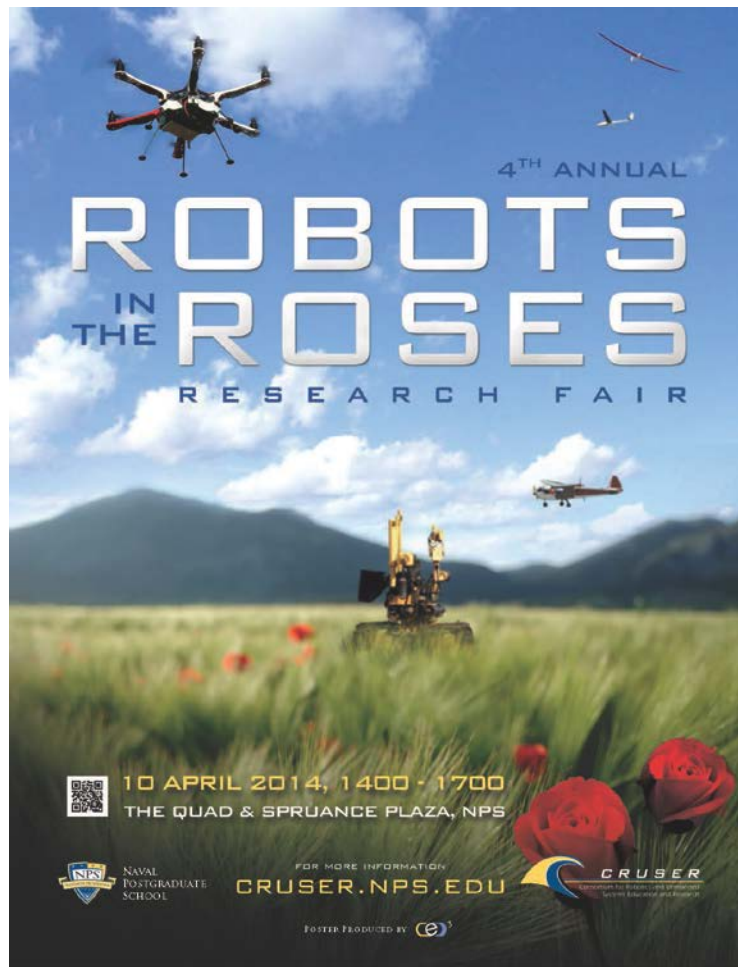


Figure 64. Robots in the Roses Research Fair, April 2014

Each year, CRUSER hosts a research fair highlighting unmanned systems activity on the NPS campus. The primary mission of this fourth annual research fair (see *Figure 64*) was again to offer the CRUSER community of interest an opportunity to share research and educational opportunities in the areas of unmanned and robotic systems. The invitation to this event was distributed to the NPS campus CRUSER community of interest to provide NPS students the opportunity to explore potential thesis topics involving emergent technology, and inspire younger students to approach their formal education in science, technology, engineering and math with zeal. Several hundred NPS staff, faculty, and students were joined by local community members and families on the NPS campus in Monterey.

3. ONR-Reserve Component Relationship

The Office of Naval Research – Reserve Component (ONR-RC) provided operational support to many CRUSER projects, programs, and events in FY14. Collaboration between CRUSER researchers at the Naval Postgraduate School (NPS) and ONR-RC began two years ago with personnel from the ONR-113 unit based at NPS, and has expanded to several additional ONR Reserve units, with 10 Reservists contributing nearly 150 days of direct operational support this FY.

In FY14, ONR-RC personnel participated in the CRUSER Technical Continuum and the 4th annual Robots in the Roses Research Fair and education outreach event where they provided feedback on NPS student research projects, led hands-on SeaPerch and tethered quad-rotor events for attendees, and answered questions on the robotics and research projects they supported. ONR-RC personnel went to sea for Wave Glider UUV research aboard R/V Fulmer, assisting in UUV launch and recovery operations. The original and largest area of ONR-RC CRUSER work has been with the Advanced Robotic Systems Engineering Laboratory (ARSENL). Reserve personnel supported Swarm UAV and other robotics and autonomy projects by constructing UAVs and other robots at NPS, serving as flight technicians and ground crews for field experimentation and flight test operations at Camp Roberts restricted airspace, checklist and procedure writing, review, and updating, construction of a prototype UAV launcher, and briefing civilian and military personnel at JIFX events. All the CRUSER and ARSENL support utilized the active duty military skills and knowledge along with the civilian technical background and experience that ONR-RC is able to provide in order to implement science and technology solutions that improve Fleet readiness.

4. Briefings

Responding to requests, CRUSER leadership has continued to brief the program to NPS campus guests. The following is a representative list (*see Table 11*):

Table 11. Representative listing of CRUSER program briefings given on request in FY14.

Date	Name	Affiliation
10 Oct 2013	Mark Gorenflo	Principal Director to the Deputy Under Secretary of the Navy for Plans, Policy, Oversight & Integration
14 Nov 2013	Prof. Stephen Tackett, SSAG Academic Associate	Space Systems Academic Group Seminar (Space Systems student outreach)
19 Nov 2013	CAPT Paul Oosterling, CO Mr. Tom Cuff, Technical Director	NAVOCEANO (Naval Oceanographic Office)
21 Nov 2013	CAPT Rob Newson	Naval Special Warfare Command

21 Nov 2013	Dr. Michael Balazs, Chief Engineer, Charlottesville Operations Mr. Jonathan Rotner, Senior Sensor System Engineer	Mitre Corporation (UAV researchers)
6 Dec 2013	CAPT Phan Phan	Commanding Officer, NR ONR NRL S&T 113
25 Apr 2014	Prof. Quek Tong Boon, Chief Defense Scientist	Singapore Ministry of Defense
25 Apr 2014	Mr. Sim Kok Wah, Head Mr. Liu Zhijian, Assistant Head Mr. Ray Tan Hang Kiang, Project Manager (Air & Land Systems) Mr. Kelvin Ang Kok Chu, Manager (Collaboration) / Staff Officer	Defense Technology Office (DTO)
25 Apr 2014	Prof. Yeo Tat Soon, Director Prof. Tang Loon Chin, Director-Designate	Temasek Defense Systems Institute (TDSI)
15 May 2014	CDR Rudy Fernandez, USN (ret.), Director of Advanced Technology Programs	Advanced Acoustic Concepts
22 May 2014	Mr. Jeff Smith, Chief Operating Officer	Bluefin Robotics
29 May 2014	John C. Brandes, Senior Program Manager	Lockheed Martin Mission Systems and Training
29 May 2014	Dr. Stephane Blouin	DRDC Atlantic Research Centre, Underwater Surveillance Communications
17 Jul 2014	Howard Reese	Arctic Submarine Laboratory

III. CONCLUSION

FY14 was the first full year in which CRUSER delved into concept exploration, providing seed money to well over 20 different projects. In addition to traditional research and experimentation, CRUSER also funded purely educational projects as is fitting with the mission of NPS.

A. PROPOSED FY15 ACTIVITIES

FY14 closes the second CRUSER Innovation Thread, continues work along the third, and begins the fourth. The following deliverables are planned for FY15:

- CRUSER will continue to fund the integration of robotics and unmanned systems issues into appropriate courses and develop educational materials that will enable the Navy and Marine Corps officers afloat to become familiar with the challenges associated with the development and operational employment of these systems.
- CRUSER will host the fourth installment in Robo-Ethics Continuing Education Series focused legal, social, cultural, and ethical issues for operators, acquisition professionals. CEUs will be offered to participants in this event (February 2015).
- CRUSER will host a fourth NPS CRUSER Technical Continuum and the fifth annual Robots in the Roses Research Fair to demonstrate technologies to aid in the concepts generated the fall workshop, showcase the current research, and host STEM events for local K-12 children (April 2015).
- CRUSER will sponsor experimentation of the most promising technologies from the TechCon held in FY13 (Quarterly 2015).
- CRUSER will sponsor a Research Expo to demonstrate the results of the first CRUSER thread: From Concept Generation to Experimentation (July 2015).
- CRUSER will sponsor NPS faculty research and experiments across the holistic topic areas not traditionally sponsored by ONR technical funds such as human resources, human systems integration, concept exploration, and others.
- CRUSER will continue to sponsor summer internships from the service academy students to work in labs across NPS.
- CRUSER will continue to fund NPS student travel to participate in research and experimentation dealing with all aspects of unmanned systems.

- CRUSER will continue Community of Interest data base generation, monthly newsletter production and distribution, and monthly community-wide meetings.
- CRUSER will continue to sponsor and participate in STEM outreach events relevant to robotics education.
- CRUSER will develop and sustain online classroom presentations to promote better understanding of the employment of robotic and unmanned systems.
- CRUSER will develop a strategy for graduate and non-graduate education across the naval enterprise with regards to robotic and unmanned systems.

B. LONG TERM PLANS

Projected to continue into FY15, CRUSER plans to catalog degree programs, short courses, and certificate programs nationwide. Integration of robotics and unmanned systems into educational programs in Naval academia such as USNA, NWC, in the NROTC, as well as in other U.S. military academic institutions. Long term plans include the creation of short course programs as identified by community of interest, and a continued effort to align curricula for interdisciplinary autonomous systems education on the NPS campus and across the naval enterprise.

APPENDIX A: PRESENTATIONS, PUBLICATIONS AND TECHNICAL REPORTS BY NPS CRUSER MEMBERS, FY11 TO PRESENT

This cumulative list of publications and scholarly presentations is representative of those completed by NPS CRUSER members since program launch in 2011. It is not meant to be all-inclusive, only give a sense of the depth and breadth of interest in CRUSER.

New for the FY14 Report

Boucher, R., W. Kang, and Q. Gong (2014). Galerkin Optimal Control for Constrained Nonlinear Problems, *American Control Conference*, Portland, OR, June 2014.

Boucher, R., W. Kang, and Q. Gong, Discontinuous Galerkin Optimal Control for Constrained Nonlinear Problems, *IEEE ICCA*, Taichung, Taiwan, June 2014.

Cichella, Choe, Mehdi, Xargay, Hovakimyan, Kaminer, Dobrokhodov, Pascoal, and Aguiar (2014). "Safe Time-Critical Cooperative Missions for Multiple Multirotor UAVs," Robotics Science and Systems. Workshop on *Distributed Control and Estimation for Robotic Vehicle Networks*, Berkeley, CA, July 2014.

Cichella, Choe, Mehdi, Xargay, Hovakimyan, Trujillo, and Kaminer (2014). "Trajectory Generation and Collision Avoidance for Time-Coordination of UAVs," *AIAA Guidance, Navigation, and Control Conference*, National Harbour, MD, January 2014.

Gardner, Maxine, LCDR, U.S. Navy (2014). "The Navy's Role in Humanitarian Assistance," *CRUSER TechCon 2014*, Monterey, California, April 2014.

Guest, Peter S. (2014). The Use of Unmanned Systems for Environmental Sampling and Enhanced Battlespace Awareness in Support of Naval Operations, *CRUSER News*, Published at the Naval Postgraduate School, Monterey CA, January 2014.

Guest, Peter S. (2014). Using UAS to Sense the Physical Environment, presented at the *NPS OPNAV N2/N6 Studies Fair Potential Theses Topics*, Naval Postgraduate School, Monterey CA, 9 January 2014

Guest, Peter S. (2014). Atmospheric Measurements From a Mini-Quad Rotor UAV – How Accurate Are Measurements Near the Surface? *CRUSER TechCon 2014*, Monterey CA, 9 April 2014.

Guest, Peter S. (2014). How accurate are measurements near the surface? A poster presented at the *CRUSER 4th Annual "Robots in the Roses" Research Fair*, Naval Postgraduate School, Monterey CA, 10 April 2014.

- Guest Peter S. (2014). Using Miniature Multi-Rotor Unmanned Aerial Vehicles for Performing Low Level Atmospheric Measurements, presented at *the 94th American Meteorological Society Annual Meeting, 18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS) Session 8: Field Experiments*, Atlanta Georgia, 5 August 2014.
- Guest, Peter S. (2014). Quantifying the Accuracy of a Quad-Rotor Unmanned Aerial Vehicle as a Platform for Atmospheric Pressure, Temperature and Humidity Measurements near the Surface, Abstract accepted for the *2014 American Geophysical Union Fall meeting*, San Francisco California, 15-19 December, 2014, abstract submitted 6 August 2014.
- Kaminer, I. (2014). "Maritime Force Protection and Herding," Presented at *ONR Science of Autonomy Workshop*, DC August 2014
- Kaminer, I. (2014). "Small UAV Autonomy: Time-Coordinated Missions and Soaring Gliders," Presented at *NASA Langley Research Center* April 2014
- King, S., W. Kang, and L. Xu (2014). Observability for Optimal Sensor Locations in Data Assimilation, *American Control Conference*, Portland, OR, June, 2014.
- Phelps, C., Q. Gong, J.O. Royset, C. Walton, and I. Kaminer (2014 *pending*). "Consistent Approximation of a Nonlinear Optimal Control Problem with Uncertain Parameters", *Automatica*, accepted for publication.
- Sanchez, Susan M. (2014). "CRUSER Data Farming Workshops," *CRUSER TechCon 2014*, Monterey, California, April 2014.
- Sanchez, Susan M., Paul J. Sanchez, and Hong Wan (2014). "Simulation Experiments: Better Insights by Design," *Summer Simulation Multiconference*, Monterey, California, July 2014.
- Sanchez, Susan M. (2014). "Simulation experiments: Better data, not just big data." *Proceedings of the 2014 Winter Simulation Conference*, forthcoming
- Song, K.S., and P.C. Chu (2014). Conceptual Design of Future Undersea Unmanned Vehicle (UUV) System for Mine Disposal. *IEEE Systems Journal*, 8 (1), 41-51.
- Thompson, Andrew, Lieutenant, U.S. Navy (2014). "Combined UUV Efforts in a Large-Scale Mine Warfare Environment" *CRUSER TechCon 2014*, Monterey, California, April 2014.
- Walton, Claire, Qi Gong, Isaac Kaminer, Johannes Royset (2014). "Optimal Motion Planning for Searching for Uncertain Targets," *2014 International Forum of Automatic Control (IFAC 2014)*

Xargay, E., R. Choe, N. Hovakimyan, and I. Kaminer (2014 *pending*). "Convergence of a PI Coordination Protocol in Networks with Switching Topology and Quantized Measurements," *Automatica*, accepted for publication.

Included in the FY13 report

Andersson, K., I. Kaminer, V. Dobrokhodov, and V. Cichella (2012). "Thermal Centering Control for Autonomous Soaring; Stability Analysis and Flight Test Results," *Journal of Guidance, Control, and Dynamics*, Vol. 35, No. 3 (2012), pp. 963-975. doi: 10.2514/1.51691

Auguston, M. and C. Whitcomb (2012). "Behavior Models and Composition for Software and Systems Architecture", *ICSSEA 2012, 24th International Conference on SOFTWARE & SYSTEMS ENGINEERING and their APPLICATIONS*, Telecom ParisTech, Paris, 23-25 October 2012. <http://icssea.enst.fr/icssea12/>

Boxerbaum, A., M. Klein, J. Kline, S. Burgess, R. Quinn, R. Harkins, R. Vaidyanatham (2012). "Design, Simulation, Fabrication and Testing of Bio-Inspired Amphibious Robot with Multiple Modes of Mobility," *Journal of Robotics and Mechatronics*, Vol. 24, No.4 August 2012.

Brutzman, D., with T. Chung, C. O'Neal, J. Ellis and L. Englehorn (2011). *Future Unmanned Naval Systems (FUNS) Wargame Competition Final Report* (NPS-USW-2011-001) released July 2011.

Carpin, S., Chung, T. H., & Sadler, B. M. (2013). Theoretical Foundations of High-Speed Robot Team Deployment. In *Proceedings of the 2013 IEEE International Conference on Robotics and Automation*.

Chitre, M. (2012). "What is the impact of propagation delay on network throughput?" *Proc.NATO Underwater Communications Conf. (UComms)*, Sestri Levante, Italy, Sept 12-14, 2012

Chitre, M., A. Mahmood, and M. Armand (2012). "Coherent communications in snapping-shrimp dominated ambient noise environments," *Proc. Acoustics 2012 Hong Kong*, vol. 131, p. 3277, May 2012

Chitre, M. (2013). "Teamwork among marine robots - advances and challenges," *Proc. WMR2013 - Workshop on Marine Robotics*, Las Palmas de Gran Canaria, Spain, February 2013

Chitre, M., I. Topor, R. Bhatnagar and V. Pallayil (2013). "Variability in link performance of an underwater acoustic network," *Proc. IEEE Oceans Conf.*, Bergen, Norway, June 2013

- Chung, T. H., Jones, K. D., Day, M. A., Jones, M., and Clement, M. R. (2013). 50 VS. 50 by 2015: Swarm Vs. Swarm UAV Live-Fly Competition at the Naval Postgraduate School. In *AUVSI North America*. Washington, D.C.
- Dono, T., and Chung, T. H. (2013). Optimized Transit Planning and Landing of Aerial Robotic Swarms. In *Proc. of 2013 IEEE Int'l. Conf. on Robotics and Automation*.
- Du Toit, N.E.; Burdick, J.W. (2012) "Robot Motion Planning in Dynamic, Uncertain Environments," *IEEE Transactions on Robotics*, Vol. 28, Issue 1, pp. 101-115, 2012.
- Economist (2013). "Underwater Networking: Captain Nemo goes online," *The Economist Magazine*, March 9, 2013
- Ellis, W., D. McLay and L. Englehorn (2013). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Warfare Innovation Workshop (WIW) 2013 After Action Report: Undersea Superiority 2050*, released May 2013.
- Gagnon, P. and J. Rice, G. Clark (2012). "Channel Modeling and Time Delay Estimation for Clock Synchronization Among Seaweb Nodes," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Gagnon, P. and J. Rice, G. A. Clark, "Clock Synchronization through Time-Variant Underwater Acoustic Channels," *Proc. NATO Underwater Communications Conference (UComms)*, Sestri Levante, Italy, 12-14 September 2012
- Green, D. (2012). "ACOMMS Based Sensing, Tracking, and Telemetry," *Proc. 3rd WaterSide Security Conference*, Singapore, 28-30 May 2012
- Guest, Peter S. (2013). "Using small unmanned aerial vehicles for undersea warfare," presented at the *NPS CRUSER Technical Continuum*, 9 April 2013.
- Guest, Peter S., Paul Frederickson, Arlene Guest and Tom Murphree (2013). "Atmospheric measurements with a small quad-rotor UAV," a poster presented at the "*Robots in the Roses*" *Research Fair*, 11 April, 2013.
- Guest Peter S. (2013). "The use of kites, tethered balloons and miniature unmanned aerial vehicles for performing low level atmospheric measurements over water, land and sea ice surfaces," abstract accepted for presentation at the *94th American Meteorological Society Annual Meeting, 18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, submitted 15 August, 2013.

- Guest, Peter S., Trident Warrior 2013 (2013). “Demonstrating the use of unmanned aerial vehicles for characterizing the marine electromagnetic propagation environment,” presented at the *NPS CRSUER Monthly Meeting*, Naval Postgraduate School, Monterey CA, 11 September 2013.
- Guest, Peter S., Trident Warrior 2013 (2013). “Evaporation and surface ducts,” presented at the *Trident Warrior 2013 Meeting*, Naval Research Laboratory, Monterey CA, 23 September, 2013.
- King, R. E. (2012). “Localization of a Mobile Node in an Underwater Acoustic Network,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Warfare Innovation Workshop (WIW) 2011 After Action Report*, released October 2011.
- Kline J. and L. Englehorn (2012). *NWDC/ CRUSER Warfare Innovation Workshop (WIW) 2012 After Action Report: Advancing the Design of Undersea Warfare*, released November 2012.
- Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Annual Report 2011: The Startup Year*, released December 2011.
- Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Annual Report 2012: The Transition Year*, released November 2012.
- Kline, J. and L. Englehorn, *Maritime Defense and Security Research Program, Final Report, 2004-2011*, Naval Postgraduate School NPS-NSI-11-01, November 2011
- Lin, K. Y., Atkinson, M. P., Chung, T. H., & Glazebrook, K. D. (2013). A Graph Patrol Problem with Random Attack Times. *Operations Research*, 61(3), 694–710.
- Mahmood, A., M. Chitre, and M. Armand (2012). “Improving PSK performance in snapping shrimp noise with rotated constellations,” *Proc. WUWNet’12: 7th ACM International Conference on Underwater Networks & Systems*, Los Angeles, CA, pp. 1-8, November 2012
- Muratore, M., Silvestrini, R. T., & Chung, T. H. (2012). Simulation Analysis of UAV and Ground Teams for Surveillance and Interdiction. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, OnlineFirst.

- Otnes, R. and V. Forsmo, H. Buen (2012). *NGAS Sea Trials*, Gulf of Taranto, Italy, September 2011, January 2012
- Otnes, R. (2012). "NILUS – An Underwater Acoustic Sensor Network Demonstrator System," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Otnes, R. and J. Rice (2013). "Underwater acoustic sensor networking in NGAS 2012 sea trial at Oslo Fjord, Norway," *Proc. 1st Underwater Acoustics Conf.*, Corfu, Greece, June 28, 2013
- Rice, J. (2011). "Maritime Surveillance in the Intracoastal Waterway using Networked Underwater Acoustic Sensors integrated with a Regional Command Center," invited presentation to *Small Vessel Security Threat Conference*, San Francisco CA, 29 September 2011
- Rice, J. (2011). "Seaweb ASW Sensor Network," FY11 year-end project report for publication in *ONR Ocean Battlespace Sensing*, December 2011
- Rice, J. and G. Wilson, M. Barlett (2012). "Deep Seaweb 1.0 Maritime Surveillance Sensor Network," *NDIA 2012 Joint Undersea Warfare Technology Spring Conference*, Undersea Sensors technical track, San Diego CA, 26-29 March 2012
- Rice, J. (2012). "Node Ranging, Localization and Tracking as Functions of Underwater Acoustic Networks," *Proc. Acoustics 2012 Hong Kong*, p. 91, 13-18 May 2012
- Rice, J. and C. Fletcher, B. Creber, B. Marn, S. Ramp, F. Bahr (2012). "Implementation of an Underwater Wireless Sensor Network in San Francisco Bay," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Rice, J. (2012). "Project MISSION – Maritime In Situ Sensing Inter-Operable Networks," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Rice, J. (2012). "Weaponized Underwater Surveillance Network," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Rice, J. and C. Fletcher, B. Creber, B. Marn, S. Ramp, F. Bahr (2012). "Implementation of an Underwater Wireless Sensor Network in San Francisco Bay," *Proc. 3rd WaterSide Security Conference*, Singapore, 28-30 May 2012
- Rice, J. (2012). "Seaweb Subsurface Sensor Network for Port Surveillance and Maritime Domain Awareness," *NMIO Technical Bulletin*, National Maritime Intelligence-Integration Office, Summer 2012 issue, Vol. 3, pp. 10-14, August 2012

- Rice, J. and M. Chitre (2013). "Maritime In Situ Sensing Inter-Operable Networks involving Acoustic Communications in the Singapore Strait," *CRUSER Technical Continuum*, Monterey, CA, April 9, 2013
- Rice, J. and M. Chitre (2013). "Maritime In Situ Sensing Inter-Operable Networks involving Acoustic Communications in the Singapore Strait," *ONR Ocean Acoustics Review*, Bay St. Louis, MS, April 24, 2013
- Rochholz, T. (2012). "Wave-Powered Unmanned Surface Vehicle Operation in the Open Ocean: A Station Keeping Asset for Distributed Netted Systems; PAC X: Transpacific Crossing of Wave Glider USVs," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012
- Rochholz, T. (2012). "Wave-Powered Unmanned Surface Vehicle as a Station-Keeping Gateway Node for Undersea Distributed Networks," presented at *NDIA Undersea Warfare Technology Conference*, Groton, CT, 24-27 September 2012
- Rothal, J. and A. Davis (2011). *A Sampling of NPS Theses and Reports on UxS*, produced by the Dudley Knox Library, released August 2011.
- Shankar, S. and M. Chitre (2013). "Tuning an underwater communication link," *Proc. IEEE OCEANS Conf.*, Bergen, Norway, June 2013
- Streenan, A. and Du Toit, N.E. (2013) "Diver Relative UUV Navigation for Joint Human-Robot Operations", *MTS/IEEE Oceans Conference*, Sept. 23-26, San Diego, CA, 2013
- Stevens, T., & Chung, T. H. (2013). Autonomous Search and Counter-Targeting using Levy Search Models. In *Proc. of 2013 IEEE Int'l. Conf. on Robotics and Automation*.
- Yakimenko, O. A., & Chung, T. H. (2012). Extending Autonomy Capabilities for Unmanned Systems with CRUSER. In *Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012)*. Brisbane, Australia.
- Yang, J. H., Kapolka, M., & Chung, T. H. (2012). Autonomy balancing in a manned-unmanned teaming (MUT) swarm attack. In *2012 International Conference on Robot Intelligence Technology and Applications*. Gwangju, Korea.
- Weiss, J.D. and Du Toit, N.E. (2013) "Real-Time Dynamic Model Learning and Adaptation for Underwater Vehicles", *MTS/IEEE Oceans Conference*, Sept. 23-26, San Diego, CA, 2013

- Xargay E., V. Dobrokhodov, I. Kaminer, A. Pascoal, N. Hovakimyan, and C. Cao (2011). “Time–Coordinated Path Following of Multiple Heterogeneous Vehicles over Time–Varying Networks,” invited paper for *IEEE Control Systems Magazine, Special Issue on UAVs and Controls*, 2011.
- Xargay, E., N.Hovakimyan, V.N. Dobrokhodov, I.I. Kaminer, C. Cao, I.M. Gregory (2012). “L1 Adaptive Control in Flight”, chapter in a book “*Progress in Aeronautics and Astronautics Series*”, AIAA, 2012.
- Xu, N., G. Cai, W. Kang, and B.M. Chen (2012). “Minimum-time trajectory planning for helicopter UAVs using dynamic optimization.” *IEEE International Conference on Systems, Man, and Cybernetics*, Seoul, South Korea, October 2012.
- Yakimenko, O.A., and Chung, T.H., “Extending Autonomy Capabilities for Unmanned Systems with CRUSER,” *Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012)*, Brisbane, Australia, 23-28 September 2012.
- Zhang, Jiexin, Yang Liu, Mikhail Auguston, Jun Sun and Jin Song Dong (2012). “Using Monterey Phoenix to Formalize and Verify System Architectures”, *19th Asia-Pacific Software Engineering Conference APSEC 2012*, Hong Kong 4 – 7 December 2012.
<http://www.comp.polyu.edu.hk/conference/APSEC2012/>

APPENDIX B: CUMULATIVE THESES AND STUDENT PROJECTS SUPPORTED

This list includes thesis and projects from FY11 forward. Unclassified NPS theses are available through the NPS Dudley Knox Library and DTIC. This list is alphabetized by student last name, and separated by year of completion (chronologically backward). As of June 2014, CRUSER has supported 99 master's theses and capstone projects, and one doctoral dissertation.

Thesis project title/subject: NPS Student (s)		
<i>Applying Cooperative Localization to Swarm UAVs using an Extended Kalman Filter</i>	Lieutenant Colonel Robert B. Davis, USMC	FY14 (SEP)
<i>Expanded Kill Chain Analysis of Manned-Unmanned Teaming for Future Strike Operations</i>	Joong Yang Lee, Republic of Singapore Air Force	FY14 (SEP)
<i>Logistics Supply of the Distributed Air Wing</i>	Mr. Chee Siong Ong, Singapore Defence Science and Technology Agency	FY14 (SEP)
<i>Assessment of Vision-Based Target Detection and Classification Solutions Using an Indoor Aerial Robot</i>	LT Nicole Ramos, USN	FY14 (SEP)
<i>Optimal Estimation of Glider's Underwater Trajectory with Depth-dependent Correction using the Regional Navy Coastal Ocean Model with Application to ASW</i>	JooEon Shim	FY14 (SEP)
<i>Relationship between the sonic layer depth and mixed layer depth identified from underwater glider with application to ASW</i>	LT Vance Villarreal, USN	FY14 (SEP)
<i>] A Modular Simulation Framework for Assessing Swarm Search Models</i>	LT Blake Wanier, USN	FY14 (SEP)
<i>The distributed air wing</i>	Systems Engineering Analysis Cross-Campus Study (SEA 20B)	FY14
<i>Sea-Shore interface robotic design</i>	LT Timothy L. Bell, USN	FY14
<i>Achieving information superiority using hastily formed networks and emerging technologies for the Royal Thai Armed Forces counterinsurgency</i>	LCDR Anthony A. Bumatay, USN; LT Grant Graeber, USN	FY14

<u>operations in Southern Thailand</u>		
<u>Droning on: American strategic myopia toward unmanned aerial systems</u>	CWO4 Carlos S. Cabello, USA	FY14
<u>Obstacle detection and avoidance on a mobile robotic platform using active depth sensing</u>	ENS Taylor K. Calibo, USN	FY14
<u>Improving operational effectiveness of Tactical Long Endurance Unmanned Aerial Systems (TALEUAS) by utilizing solar power</u>	LT Nahum Camacho, Mexican Navy	FY14
<u>Increasing the endurance and payload capacity of unmanned aerial vehicles with thin-film photovoltaics</u>	Capt Seamus B. Carey, USMC	FY14
<u>Power transfer efficiency of mutually coupled coils in an aluminum AUV hull</u>	LCDR James M. Cena, USN	FY14
<u>Tropical cyclone reconnaissance with the Global Hawk: operational thresholds and characteristics of convective systems over the tropical Western North Pacific</u>	LCDR David W. Damron, USN	FY14
<u>Cost-effectiveness analysis of aerial platforms and suitable communication payloads</u>	LCDR Randall E. Everly, USN; LT David C. Limmer, USN	FY14
<u>Characterization parameters for a three degree of freedom mobile robot</u>	LT Jessica L. Fitzgerald, USN	FY14
<u>Computer-aided detection of rapid, overt, airborne, reconnaissance data with the capability of removing oceanic noises</u>	LT James R. Fritz, USN	FY14
<u>A data-driven framework for rapid modeling of wireless communication channels</u> (PhD dissertation)	Douglas Horner, NPS	FY14
<u>An analysis of the defense acquisition strategy for unmanned systems</u>	Maj Courtney David Jones, USMC	FY14
<u>Terrain aided navigation for REMUS autonomous underwater vehicle</u>	ENS Jacob T. Juriga, USN	FY14
<u>Investigation of acoustic vector sensor data processing in the presence of highly variable bathymetry</u>	LT Timothy D. Kubisak, USN	FY14

<u>U.S. Army Unmanned Aircraft Systems (UAS)â€™ a historical perspective to identifying and understanding stakeholder relationships</u>	Donald R. Lowe, DON (Civ); Holly B. Story, DOA (Civ); Matthew B. Parsons, DOA (Civ)	FY14
<u>Preliminary design of an autonomous underwater vehicle using multi-objective optimization</u>	LCDR Sotirios Margonis, Hellenic Navy	FY14
<u>Da Vinci's children take flight: unmanned aircraft systems in the homeland</u>	Jeanie Moore, FEMA Office of External Affairs	FY14
<u>A comparison of tactical leader decision making between automated and live counterparts in a virtual environment</u>	MAJ Scott A. Patton, USA	FY14
<i>High Energy Laser Employment in Self Defense Tactics on Naval Platforms [RESTRICTED]</i>	LT Brett Robblee, USN	FY14
<u>Optimal deployment of unmanned aerial vehicles for border surveillance</u>	First LT Volkan Sözen, Turkish Army	FY14
<u>Domestic aerial surveillance and homeland security: should Americans fear the eye in the sky?</u>	LCDR Barclay W. Stamey, USN	FY14
<u>Lightening the load of a USMC Rifle Platoon through robotics integration</u>	LT Sian E. Stimpert, USN	FY14
<u>Small Tactical Unmanned Aerial System (STUAS) Rapid Integration and fielding process (RAIN)</u>	Christopher Ironhill, Bryan Otis, Frederick Lancaster, Angel Perez, Diana Ly, and Nam Tran	FY13 (SEP)
<u>Development and validation of a controlled virtual environment for guidance, navigation and control of quadrotor UAV</u>	Junwei Choon, Singapore Technologies Aerospace	FY13 (SEP)
<u>An examination of the collateral psychological and political damage of drone warfare in the FATA region of Pakistan</u>	Judson J. Dengler, U.S. Secret Service	FY13 (SEP)
<u>Integrating Unmanned Aerial Vehicles into surveillance systems in complex maritime environments</u>	LCDR Georgios Dimitriou, Hellenic Navy	FY13 (SEP)
<u>Improving the Army's joint platform allocation tool (JPAT)</u>	LT John P. Harrop, USN	FY13 (SEP)
<u>Active shooters: is law enforcement ready for a</u>	Captain Joel M. Justice, Los	FY13

<u>Mumbai style attack?</u>	Angeles Police Department	(SEP)
<u>The rise of robots and the implications for military organizations</u>	Captain Zhifeng Lim, Singapore Armed Forces	FY13 (SEP)
<u>Dynamic bandwidth provisioning using Markov chain based on RSVP</u>	Lieutenant Junior Grade Yavuz Sagir, Turkish Navy	FY13 (SEP)
<u>Systems engineering and project management for product development: optimizing their working interfaces</u>	Mariela I. Santiago, NUWC Newport	FY13 (SEP)
<u>Dynamic towed array models and state estimation for underwater target tracking</u>	LCDR Zachariah H. Stiles, USN	FY13 (SEP)
<u>Diver relative UUV navigation for joint human-robot operations</u>	LT Andrew T. Streenan, USN	FY13 (SEP)
<u>Closing the gap between research and field applications for multi-UAV cooperative missions</u>	Harn Chin Teo, ST Aerospace Ltd.	FY13 (SEP)
<u>Enhancing entity level knowledge representation and environmental sensing in COMBATXXI using unmanned aircraft systems</u>	MAJ James C. Teters,II, USA	FY13 (SEP)
<u>Real-time dynamic model learning and adaptation for underwater vehicles</u>	LT Joshua D. Weiss, USN	FY13 (SEP)
<u>2024 Unmanned undersea warfare concept</u>	Systems Engineering Analysis Cross-Campus Study (SEA 19A)	FY13
<u>Mobility modeling and estimation for delay tolerant unmanned ground vehicle networks</u>	LT Timothy M. Beach, USN	FY13
<u>Effectiveness of Unmanned Aerial Vehicles in helping secure a border characterized by rough terrain and active terrorists</u>	First Lieutenant Begum Y. Ozcan, Turkish Air Force	FY13
<u>Integration Of Multiple Unmanned Systems In An Urban Search And Rescue Environment</u>	Boon Heng Chua, Defence Science and Technology Agency, Singapore	FY13
<i>Analysis of Ocean Variability in the South China Sea for Naval Operations</i>	LT Mary Doty	FY13
<i>Computer Aided Mine Detection Algorithm for Tactical Unmanned Aerial Vehicle (TUAV)</i>	LT James Fritz	FY13

<u>UAV swarm tactics: an agent-based simulation and Markov process analysis</u>	Captain Uwe Gaertner, German Army	FY13
<u>Extending the endurance of small unmanned aerial vehicles using advanced flexible solar cells</u>	Capt Christopher R. Gromadski, USMC	FY13
<i>The Optimal Employment and Defense of a Deep Seaweb Acoustic Network for Submarine Communications at Speed And Depth using a Defender-Attacker-Defender Model</i>	LT Andrew Hendricksen, USN	FY13
<u>Integrating Coordinated Path Following Algorithms To Mitigate The Loss Of Communication Among Multiple UAVs</u>	LT Kyungnho Kim, USN	FY13
<i>Intelligence fused Oceanography for ASW using Unmanned Underwater Vehicles (UUV) [SECRET]</i>	LCDR Paul Kutia	FY13
<u>Digital Semaphore: technical feasibility of QR code optical signaling for fleet communications</u>	LCDR Andrew R. Lucas, USN (thesis award winner)	FY13
<u>Effects Of UAV Supervisory Control On F-18 Formation Flight Performance In A Simulator Environment</u>	LCDR Eric L. McMullen, USN and MAJ Brian Shane Grass, U.S. Army	FY13
<i>Analysis of Bioluminescence and Optical Variability in the Arabian Gulf and Gulf of Oman for Naval Operations[Restricted]</i>	LT Thai Phung	FY13
<u>Digital semaphore: tactical implications of QR code optical signaling for fleet communications</u>	LT Stephen P. Richter, USN (thesis award winner)	FY13
<u>Design and hardware-in-the-loop implementation of optimal canonical maneuvers for an autonomous planetary aerial vehicle</u>	LT Marta Savage, USN	FY13
<u>Improving UXS network availability with asymmetric polarized mimo</u>	Robert N. Severinghaus	FY13
<u>Modeling and simulation for a surf zone robot</u>	LT Eric Shuey, USN and LT Mika Shuey, USN	FY13
<u>Analysis of Nondeterministic Search Patterns for Minimization of UAV Counter-Targeting</u>	LT Timothy S. Stevens, USN	FY13
<u>A human factors analysis of USAF remotely piloted aircraft mishaps</u>	Maj Matthew T. Taranto, USAF	FY13

<u><i>A systems engineering analysis of unmanned maritime systems for U.S. Coast Guard missions</i></u>	LT James B. Zorn, USCG	FY13
<u><i>Tailorable Remote Unmanned Combat Craft (TRUCC)</i></u>	Systems Engineering Analysis Cross-Campus Study (SEA 18B)	FY12
<u><i>Autonomous Dirigible Airships: a Comparative Analysis and Operational Efficiency Evaluation for Logistical Use in Complex Environments</i></u>	LT Brian Acton, USN LT David Taylor, USN	FY12
<u><i>An Interpolation Approach to Optimal Trajectory Planning for Helicopter Unmanned Aerial Vehicles</i></u>	Maj Jerrod Adams, U.S. Army	FY12
<u><i>Implementation of Autonomous Navigation And Mapping Using a Laser Line Scanner on a Tactical Unmanned Vehicle</i></u>	Maj Mejdi Ben Ardhaoui, Tunisian Army	FY12
<u><i>An Analysis of Undersea Glider Architectures and an Assessment of Undersea Glider Integration into Undersea Applications</i></u>	Mr William P. Barker	FY12
<u><i>Integration of an Acoustic Modem onto a Wave Glider Unmanned Surface Vehicle</i></u>	ENS Joseph Beach, USN	FY12
<u><i>Investigation of Propagation in Foliage Using Simulation Techniques</i></u>	LCDR Chung Wei Chan, Republic of Singaporean Navy	FY12
<u><i>Joint Sensing/Sampling Optimization for Surface Drifting Mine Detection with High-Resolution Drift Model</i></u>	LT Kristie M. Colpo, USN	FY12
<u><i>Does China Need A “String Of Pearls”?</i></u>	Capt Martin Conrad, USAF	FY12
<u><i>Unmanned Aircraft Systems: A Logical Choice For Homeland Security Support</i></u>	Maj Bart Darnell, USAF	FY12
<u><i>Multi-Agent Task Negotiation Among UAVs</i></u>	Mr. Michael Day	FY12
<u><i>Optimized Landing of Autonomous Unmanned Aerial Vehicle Swarms</i></u>	Maj Thomas F. Dono, USMC	FY12
<u><i>An Analysis of the Manpower Impact of Unmanned</i></u>	LT Thomas Futch, USN	FY12

<u>Aerial Vehicles (UAV's) on Subsurface Platforms</u>		
<u>Clock Synchronization through Time-Variant Underwater Acoustic Channels</u>	LCdr Pascal Gagnon, Canada	FY12
<u>UAV to UAV Target Detection And Pose Estimation</u>	Capt Riadh Hajri, Tunisian Air Force	FY12
<u>A Cost-Benefit Analysis Of Fire Scout Vertical Takeoff And Landing Tactical, Unmanned, Aerial Vehicle (VTUAV) Operator Alternatives</u>	CDR Kevin L. Heiss, USN	FY12
<u>Autonomous Parafoils: Toward a Moving Target Capability</u>	CDR Chas Hewgley, USN	FY12
<u>Design and Development of Wireless Power Transmission for Unmanned Air Vehicles</u>	Captain Chung-Huan Huang, Taiwan (Republic of China) Army	FY12
<u>Adaptive Speed Controller for the Seafox Autonomous Surface Vessel</u>	LT Michael A. Hurban, USN	FY12
<u>Coordination and Control for Multi-Quadrotor UAV Missions</u>	LT Levi C. Jones, USN	FY12
<u>An Analysis of the Best-Available, Unmanned Ground Vehicle in the Current Market, with Respect to the Requirements of the Turkish Ministry of National Defense</u>	LT Serkan Kilitci, Turkish Navy LT Muzaffer Buyruk, Turkish Army	FY12
<u>Underwater Acoustic Network As A Deployable Positioning System</u>	ENS Rebecca King, USN	FY12
<u>Business Case Analysis of Medium Altitude Global ISR Communications (MAGIC) UAV System</u>	Ramesh Kolar	FY12
<u>The EP-3E vs. the BAMS UAS An Operating and Support Cost Comparison</u>	LT Colin G. Larkins, USN	FY12
<u>Global Versus Reactive Navigation for Joint UAV-UGV Missions in a Cluttered Environment</u>	ENS Michael Martin, USN	FY12
<u>Bridging Operational and Strategic Communication Architectures Integrating Small Unmanned Aircraft Systems as Airborne Tactical Communication</u>	Maj Jose D. Menjivar, USMC	FY12

<u>Vertical Nodes</u>		
<u>The Aerodynamics of a Maneuvering UCAV 1303 Aircraft Model and its Control through Leading Edge Curvature Change</u>	ENS Christopher Medford, USN	FY12
<u>Future of Marine Unmanned Aircraft Systems (UAS) in Support of a Marine Expeditionary Unit (MEU)</u>	Maj Les Payton, USMC	FY12
<u>Wave-Powered Unmanned Surface Vehicle as a Station-Keeping Gateway Node for Undersea Distributed Networks</u>	LT Timothy Rochholz	FY12
<u>GSM Network Employment on a Man-Portable UAS</u>	LT Darren J. Rogers, USN	FY12
<u>New Navy Fighting Machine in the South China Sea</u>	LT Dylan Ross, USN LT Jimmy Harmon, USN	FY12
<u>Business Case Analysis of Cargo Unmanned Aircraft System (UAS) Capability in Support of Forward Deployed Logistics in Operation Enduring Freedom (OEF)</u>	LT Jason Staley, USN Capt Troy Peterson, USMC	FY12
<u>Application Of An Entropic Approach To Assessing Systems Integration</u>	Mr Hui Fang Evelyn Tan, Republic of Singapore	FY12
<u>Advanced Undersea Warfare Systems</u>	Systems Engineering Analysis Cross-Campus Study (SEA 17B)	FY11
<u>The Dispersal Of Taggant Agents With Unmanned Aircraft Systems (UAS) In Support Of Tagging, Tracking, Locating, And Identification (TTLI) Operations</u>	Capt Dino Cooper, USMC	FY11
<u>Adaptive Reception for Underwater Communications</u>	LTJG Spyridon Dessalermos, Hellenic Navy (Greece)	FY11
<u>The Design and Implementation of a Semi-Autonomous Surf-Zone Robot Using Advanced Sensors and a Common Robot Operating System</u>	LT Steve Halle, USN LT Jason Hickle, USN	FY11
<u>Probabilistic Search on Optimized Graph Topologies</u>	Major Christian Klaus, German Army	FY11

<u><i>Brave New Warfare Autonomy in Lethal UAVS</i></u>	LT Matthew Larkin, USN	FY11
<u><i>Agent-based simulation and analysis of a defensive UAV swarm against an enemy UAV swarm</i></u>	Lieutenant Mauricio M. Munoz, Chilean Navy	FY11
<u><i>Derivation of River Bathymetry Using Imagery from Unmanned Aerial Vehicles (UAV)</i></u>	LT Matthew Pawlenko, USN	FY11
<u><i>Design Requirements For Weaponizing Man-portable UAS In Support Of Counter-sniper Operations</i></u>	Maj Derek Snyder, USMC	FY11
<u><i>Self-propelled semi-submersibles the next great threat to regional security and stability</i></u>	LT Lance J Watkins, USN	FY11

APPENDIX C: COMMUNITY

This is a representative listing of the CRUSER community of interest in the third program year. It is not meant to be inclusive, but is included to demonstrate depth and breadth of interest.

USN and USMC Organizations:	COMPACFLT
	Marine Corps Combat Development Command, Operations Analysis Division (MCCDC)
	NAVAIR
	Naval Research Laboratory (NRL)
	NAVSEA
	Naval Special Warfare Command (NSW)
	Naval Surface Warfare Center (NSWC) Carderock
	Naval Surface Warfare Center (NSWC) Crane
	Naval War College (NWC)
	Naval Undersea Warfare Command (NUWC) Newport
	Navy Office of General Counsel
	Navy PEO Littoral and Mine Warfare (LMW), PMS 408
	Navy Reserves
	Navy Warfare Development Command (NWDC)
	Office of Naval Intelligence (ONI)
	Office of Naval Research (ONR)
	Office of Naval Research - Global (ONR-G)
	Space Systems Center, Pacific (SSC Pacific)
	U.S. Naval Academy (USNA)
Other Government Organizations & Institutes:	AFIAA, USAF
	Army Research Laboratory (ARL), USA
	COMCARSTRKGRU TWO
	COMPHIBRON EIGHT
	COMSUBDEVRON FIVE
	CSDS-12
	Defense Advanced Research Projects Agency (DARPA)
	Department of Energy
	HQ TRADOC
	I MEF
	Joint Ground Robotics Enterprise (JGRE OUSD)
	Joint Unmanned Aerial Systems - Center of Excellence
	Lawrence Livermore National Laboratory (LLNL)
	Marine Corp Warfighting Lab
	MCIOC
	National Aeronautics and Space Administration (NASA)
	National Oceanographic and Atmospheric Administration (NOAA)

	NAVSEA
	Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD(AT&L))
	OPNAV
	PEO C4I
	Robotic Systems Joint Project Office
	SOCAFRICA
	SSC Atlantic
	State of Wisconsin
	SUBFOR
	U.S. Air Force Academy, USAF
	U.S. Army Robotics Center of Excellence
	U.S. Army Unmanned Aerial Systems - Center of Excellence
	U.S. Army Tank-automotive and Armaments Command (TACOM)
	U.S. Army War College
	USFFC
	USMC Pentagon
	U.S. Military Academy (USMA)
	USS Chung-Hoon
	USSTRATCOM
Non-Government Organizations:	
	Autonomous Undersea Vehicle Applications Center (AUVAC)
	Institute for Religion and Peace
	Monterey Bay Aquarium Research Institute (MBARI)
International	UK National Oceanography Centre
	Agency for Defence Development (ADD)
	French Air Force Academy
	LIG Nex1, South Korea
Academia:	Netherlands Defence Academy (NLDA), Eindhoven University of Technology (TU/e), School of Innovation Sciences: Philosophy & Ethics, TNO and Delft University of Technology
	American University
	Arizona State University
	Auburn University
	California State University at Monterey Bay (CSUMB)
	Carnegie Mellon University
	Georgia Institute of Technology
	Case Western Reserve U
	CSULB HHS
	Drexel University
	Georgia Tech Research Institute (GTRI)
	Indiana State University
	The Johns Hopkins University Applied Physics Laboratory (JHU/APL)

	Kansas State University (KSU)
	Macquarie University
	Marine Advanced Technology Education (MATE)
	Massachusetts Institute of Technology (MIT)
	Memorial University of Newfoundland
	MIT Lincoln Laboratory
	New Mexico State University
	Northeastern University
	Northwestern University
	Penn State University Applied Physics Laboratory (PSU/APL)
	Rensselaer Polytechnic Institute
	SUNY Stony Brook
	University of Alaska
	University of Idaho
	University of Iowa
	University of Hawaii
	University of New Brunswick
	University of North Dakota
	University of Notre Dame
	University of Oklahoma
	University of South Florida
Industry:	Virginia Tech
	AAI Corporation
	Advanced Acoustics Concepts
	Aerojet
	Aerovironment
	Alidade, Inc.
	Alpha Research & Technology, Inc.
	Applied Physical Sciences Corp.
	Applied Research Associates, Inc.
	Aurora Flight Sciences
	AUVSI Foundation
	BAE Systems
	Battelle
	BBN Technologies
	Bell Helicopter Textron, Inc.
	Bluefin Robotics Corporation
	Boeing
	Booz Allen Hamilton
	Boston Engineering Corporation
	Charles River Analytics
	Charles Stark Draper Laboratory
	Comphydro, Inc.
	Compsim LLC
	Computer Systems Center, Inc. (CSCI)
	Comtech Solutions, LLC
	CS-Solutions, Inc.

	Daniel H. Wagner Associates
	David Ricker Group, LLC
	Desert Star Systems
	Draper Lab
	Duzuki
	Dynetics
	ELG, Inc.
	EQC, Inc.
	FIRST Robotics
	General Atomics
	General Dynamics Information Technology (GDIT)
	General Dynamics Electric Boat
	General Dynamics Land Systems
	Hydr0 Source, LLC
	Innovative Vessel Design
	Insitu
	Institute for Homeland Security Solutions
	iRobot
	Joint Venture Monterey Bay
	Lockheed Martin
	McKinsey & Co.
	Makani Power, Inc.
	Maritime Applied Physics Corp. (MAPC)
	MDA Corporation
	MITRE
	MRU Systems
	NAVPRO Consulting LLC
	Neptune Minerals
	NNS
	Northrop Grumman
	NWUAV Propulsion Systems
	Oceaneering Technologies
	Ocog, Inc.
	Orca Maritime, Inc.
	Odyssey Marine Exploration
	Physical Sciences, Inc.
	QinetiQ
	The Radar Revolution
	Raytheon
	RIX Industries
	Rockwell Collins, Inc.
	Rolls Royce
	SAGE Solutions Group, Inc.
	SAIC, Inc.
	Soliton Ocean Services, Inc.
	Sparton Defense and Security
	Spatial and Spectral Research

	Spiral Technology, Inc.
	SRI International
	ST Aerospace
	Strategic Defense Solutions, LLC
	Systems Planning & Analysis, Inc.
	Tactical Air Support, Inc.
	TASC
	Tech Associates, LLC
	Teledyne RDI
	United Technologies Research Center (UTRC)
	Unmanned Vehicle Systems Consulting, LLC
	Vehicle Control Technologies, Inc.
Other:	Monterey County Herald
	The Salinas Californian

APPENDIX D: CRUSER FY14 CALL FOR PROPOSALS



From Technical to Ethical.....From Concept Generation to Experimentation...

<http://CRUSER.nps.edu>

CRUSER Call for Proposals FY14

PROPOSALS DUE DATE:	16 Sept 13
Selection Date:	10 Oct 2013
Funding Period:	1 Oct 13 – 31 Dec 14
Funding Levels:	\$75,000 - \$125,000

This is a combined FY14 CRUSER call for proposals with two tracks: Research and Education.

Research Goal: The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) at the Naval Postgraduate School provides a collaborative environment for the advancement of educational and research endeavors across the Navy and Marine Corps. The establishment of CRUSER seeks to align efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, and supporting innovation through directed programs of operational experimentation.

Education Goal: CRUSER strives to increase knowledge and understanding of robotics and unmanned systems through the innovative use of technology combined with established concepts of education. CRUSER Education Thread Concepts are designed to encourage contributions to this educational goal through the development of educational devices that can help achieve deep intellectual penetration across a broad audience base while maintaining a common theme focused on robotics and unmanned systems. The development and use of robotics and unmanned systems involve a vast and complex web of academic disciplines. Technical and ethical issues must be combined with knowledge and understanding of such diverse topics as human systems integration, information processing, information display, training, logistics, acquisition,

development, C2 architectures, legal constraints, and levels of autonomy versus mission risk. These are but a small sample of potential topics that need to be addressed.

Anticipated Funding Amount: Funding has not yet been received for FY14; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the new fiscal year. It is anticipated that a minimum of \$750k will be available for FY14 CRUSER funded research and \$500k will be available for FY14 CRUSER funded education.

- *Student travel and support is budgeted separately, so proposals should include anticipated student travel funding requirements, but not include that amount in the total requested*

Research Focus Areas: CRUSER Innovation Thread: Advancing Undersea Operations

- a) **Decoys and military deception (MILDEC):** Designs to obfuscate targeting or cloud the enemy's operational picture - such as a USV swarm fleet or acoustic deception by unmanned systems.
- b) **Vessel tagging:** For domain awareness and tracking - such as remora tag with hydro-fan generator.
- c) **Non-lethal kinetic effects:** Generation of non-lethal stopping tactics and mechanisms - such as condenser fouling agents.
- d) **Undersea positioning, navigation and timing:** For navigation accuracy and domain awareness as an alternative to GPS and surrogate for underwater use.
- e) **Undersea "garage":** Autonomous docking, power generation and transfer, deployment and to extend time on station.
- f) **Hybrid unmanned vehicles:** Multi-domain vehicles that transition between domains.
- g) **Crowd-sourcing:** Leveraging white shipping, regional fishing fleet and other entities to meet mission data collection needs.
- h) **Natural low frequency search methods:** leverage the earth's natural electromagnetic spectrum for search based on receiving anomalies caused by man-made platforms as they disturb various fields and emissions
- i) **Re-seeding energy:** induction transfer of energy to LDUUV payload, and LDUUV induction to fielded sensors
- j) **Using UUVs to aid in submarine minefield navigation:** also called undersea "Sled Dogs", or "Cat Whiskers" uses a "dynamic Q route" using Q from the stochastic model
- k) **Wide area decoy:** surface launched drone deployment using many inexpensive gliders ("flocks") deployed from LDUUV via a balloon to altitude – add reflectors to confuse adversary

Education Focus Areas:

- a) **Content:** Develop course or lecture content modules that focus on specific aspects of the CRUSER mission set. These modules may be delivered presentations, videos,

demonstrations, simulations, or any format that optimizes opportunities to reach, inform and educate intended audiences.

b) **Education Sequencing Plans:**

- a. **Virtual lecture series:** Develop sequencing plans for distribution of synchronous and asynchronous web-based lectures that support the major areas of the CRUSER mission
- b. **Physical lecture series:** Develop sequencing plans for distribution of face-to-face lectures that support various areas of CRUSER mission
- c) **Distributed information chunking:** Develop optimal solutions for presenting complex concepts to globally distributed personnel with limited chunks of time to spend online.
- d) **Audience Identification:** Analyze the intended audience for CRUSER initiatives and determine the appropriate medium and level of detail for each demographic division

Required Documents:

1. 1-page executive summary – template provided on <http://CRUSER.nps.edu>
2. 5-7 page proposal – template with key areas provided on <http://CRUSER.nps.edu>
3. Research Office Budget Form
4. Research Office Proposal Routing form (including chair & dean signature)

Submission Procedures:

- FY14 CRUSER Proposals and supporting documents should be submitted to cruser@nps.edu (Lisa Trawick, CRUSER Operations Manager). Do not submit through the research office.

Review and Selection Board: Proposals will be evaluated by a panel of reviewers co-chaired by the Dean of Research and the CRUSER Director. Any member of the CRUSER coordination group submitting a funding proposal will not serve on the panel.

Proposal Evaluation Criteria:

- 1) Student involvement
- 2) Interdisciplinary, interagency, and partnerships with naval labs
- 3) Partnerships with other sponsors' funding
- 4) Research related to various unmanned systems' categories:
 - a. Technical
 - b. Organization and Employment
 - c. Social, Cultural, Political, Ethical and Legal
 - d. Experimentation
 - e. Defense against threat UxS capabilities
- 5) New research area (Seed money to attract other contributors)
- 6) Related to CRUSER innovation thread: Advancing Undersea Operations
- 7) Alignment with SECNAV's DoN Unmanned Systems Goals (see *CRUSER Charter* memo)

- 8) Researchers are members of the CRUSER Community of Interest
- 9) Proposals should aim to make an immediate impact on the community(\$75k - \$125k)

Notification: PIs will be notified if their CRUSER research proposal was selected when FY14 funds are available.

Funding: A sub-JON will be established for each funded research proposal

Faculty members who receive CRUSER Research and Experimentation or Education funds are expected to be members of CRUSER AND fully active in supporting CRUSER's goals to include: monthly meeting attendance, presentations, CRUSER News articles, displays at Robots in the Roses, and participation at other CRUSER sponsored events, including presentations to ONR during the annual ONR CRUSER visit.

APPENDIX E: CRUSER FY15 CALL FOR PROPOSALS

The FY15 call for proposals was distributed as two distinct documents: 1) research track, and 2) education track. The call for proposals was released in early September 2014, and proposals will be reviewed and selected for funding in early October 2014.

CRUSER CALL FOR PROPOSALS FY15: RESEARCH TRACK



<http://CRUSER.nps.edu>

PROPOSALS DUE DATE:

Selection Date:

22 Sept 14

Funding Period:

1 Oct 2014

Funding Levels:

1 Oct 14 – 30 Nov 15

Proposal Types:

\$75,000 - \$150,000

Single-Year Proposals

Research Goal: The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) at the Naval Postgraduate School provides a collaborative environment for the advancement of educational and research endeavors involving unmanned systems across the Navy and Marine Corps. CRUSER seeks to align efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, and supporting innovation through directed programs of operational experimentation.

Anticipated Funding Amount: Funding has not yet been received for FY15; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the new fiscal year. It is anticipated that a minimum of \$2.1 million will be available for FY15 CRUSER funded research.

- *Student travel and support is budgeted separately, so proposals should include anticipated student travel funding requirements, but not include that amount in the total requested*

Research Focus Areas: CRUSER Innovation Thread 3: Distributing Future Naval Air and Surface Forces

- a) Re-seeding energy
- b) C2/3 Concepts
- c) Wide area decoy
- d) Using UUVs to aid in submarine minefield navigation
- e) Natural low frequency search methods
- f) Deception and Weather Concepts
- g) Asset Distribution and Employment Concepts

NOTE: Proposals for topics related to ANY robotic/unmanned systems area will be considered.

Classification Level: Unclassified (Preferred)

Required Documents:

- 5. 1-page executive summary – template provided on <http://CRUSER.nps.edu>
- 6. 5-7 page proposal – template with key areas provided on <http://CRUSER.nps.edu>
- 7. Research Office Budget form
- 8. Research Office Proposal Routing form (including chair and dean signature)
- 9. Quad Chart

Submission Procedures:

- FY15 CRUSER Proposals and supporting documents should be submitted to cruser@nps.edu (Lisa Trawick, CRUSER Operations Manager). Do not submit through the Research Office.

Review and Selection Board: Proposals will be evaluated by a panel of reviewers co-chaired by the Dean of Research and the CRUSER Director. Any member of the CRUSER coordination group submitting a funding proposal will not serve on the panel.

Proposal Evaluation Criteria:

- 10) Student involvement
- 11) Interdisciplinary, interagency, and partnerships with naval labs
- 12) Partnerships with other sponsors' funding
- 13) Research related to various unmanned systems' categories:
 - a. Technical
 - b. Organization and Employment
 - c. Social, Cultural, Political, Ethical and Legal
 - d. Experimentation
 - e. Defense against threat UxS capabilities
- 14) New research area (seed money to attract other contributors)
- 15) Research topics related to ANY robotic and unmanned systems area may be proposed, proposals related to any CRUSER innovation thread are preferred. (See website)
- 16) Alignment with SECNAV's DON Unmanned Systems Goals (see *CRUSER Charter* memo)

- 17) Researchers are members of the CRUSER Community of Interest
- 18) Proposals should aim to make an immediate impact on the community (\$75k - \$150k)

Notification: Principal Investigators (PIs) will be notified if their CRUSER research proposal was selected when FY15 funds are available.

Faculty members who receive CRUSER funds are expected to be members of CRUSER AND fully active in supporting CRUSER's goals to include (but not limited to):

- Monthly meeting attendance
- Presentations
- CRUSER News articles
- Participation at other CRUSER sponsored events, including presentations to ONR during the annual ONR CRUSER visit.
- Contributions to the CRUSER Annual Report
- Providing updated labor plans and budget projections as requested

CRUSER CALL FOR PROPOSALS FY15: EDUCATION TRACK



<http://CRUSER.nps.edu>

PROPOSALS DUE DATE:

22 Sept 14

Selection Date:

1 Oct 2014

Funding Period:

1 Oct 14 – 30 Nov 15

Funding Levels:

\$75,000 - \$150,000

Proposal Type:

Single-Year Proposals

Education Goal: The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) strives to increase knowledge and understanding of robotics and unmanned systems through the innovative use of technology combined with established concepts of education. CRUSER Education Thread Concepts are designed to encourage contributions to this educational goal through the development of educational devices that can help achieve deep intellectual penetration across a broad audience base while maintaining a common theme focused on robotics and unmanned systems. The development and use of robotics and unmanned systems involve a vast and complex web of academic disciplines. Technical and ethical issues must be combined with knowledge and understanding of such diverse topics as human systems integration, information processing, information display, training, logistics, acquisition, development, C2 architectures, legal constraints, and levels of autonomy versus mission risk. These are but a small sample of potential topics that need to be addressed.

Anticipated Funding Amount: Funding has not yet been received for FY15; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the new fiscal year. It is anticipated that a minimum of \$900k will be available for FY15 CRUSER funded education proposals.

- *Student travel and support is budgeted separately, so proposals should include anticipated student travel funding requirements, but not include that amount in the total requested*

Education Focus Areas:

- e) **Content:** Develop course or lecture content modules that focus on specific aspects of the CRUSER mission set. These modules may be delivered presentations, videos, demonstrations, simulations, or any format that optimizes opportunities to reach, inform and educate intended audiences.

- f) **Education Sequencing Plans:**
 - a. **Virtual lecture series:** Develop sequencing plans for distribution of synchronous and asynchronous web-based lectures that support the major areas of the CRUSER mission
 - b. **Physical lecture series:** Develop sequencing plans for distribution of face-to-face lectures that support various areas of CRUSER mission
- g) **Distributed information chunking:** Develop optimal solutions for presenting complex concepts to globally distributed personnel with limited chunks of time to spend online.
- h) **Audience Identification:** Analyze the intended audience for CRUSER initiatives and determine the appropriate medium and level of detail for each demographic division

Classification Level: Unclassified

Required Documents:

- 10. 1-page executive summary – template provided on <http://CRUSER.nps.edu>
- 11. 5-7 page proposal – template with key areas provided on <http://CRUSER.nps.edu>
- 12. Research Office Budget form
- 13. Research Office Proposal Routing form (including chair and dean signature)
- 14. Quad Chart

Submission Procedures:

- FY15 CRUSER proposals and supporting documents should be submitted to cruser@nps.edu (Lisa Trawick, CRUSER Operations Manager). Do not submit through the Research Office.

Review and Selection Board: Proposals will be evaluated by a panel of reviewers co-chaired by the Dean of Research and the CRUSER Director. Any member of the CRUSER coordination group submitting a funding proposal will not serve on the panel.

Proposal Evaluation Criteria:

- 19) Student involvement
- 20) Interdisciplinary, interagency, and partnerships with naval labs
- 21) Partnerships with other sponsors' funding
- 22) Proposer is a teaching faculty member
- 23) Related to a CRUSER innovation thread. (See website)
- 24) Alignment with SECNAV's DON Unmanned Systems Goals (see *CRUSER Charter* memo)
- 25) Researchers are members of the CRUSER Community of Interest
- 26) Proposals should aim to make an immediate impact on the community (\$75k - \$150k)

Notification: Principal Investigators (PIs) will be notified if their CRUSER education proposal was selected when FY15 funds are available.

Faculty members who receive CRUSER funds are expected to be members of CRUSER AND fully active in supporting CRUSER's goals to include (but not limited to):

- Monthly meeting attendance
- Presentations
- CRUSER News articles
- Participation at other CRUSER sponsored events, including presentations to ONR during the annual ONR CRUSER visit.
- Contributions to the CRUSER Annual Report
- Providing updated labor plans and budget projections as requested

APPENDIX F: CRUSER MANAGEMENT TEAM

DIRECTOR: Dr. Raymond R. Buettner Jr. is an Associate Professor in the Information Sciences Department at the Navy Postgraduate School and the NPS Director of Field Experimentation. Dr Buettner served 10 years as Naval Nuclear Propulsion Plant Operator while earning his Associate's and Bachelor's degrees. He holds a Master of Science in Systems Engineering degree from the Naval Postgraduate School and a Doctorate degree in Civil and Environmental Engineering from Stanford University. From 2003 to 2005, Dr. Buettner served on the faculty at the Naval Postgraduate School (NPS) and was the Information Operations Chair. He is the Chair of Technical Operations, in which he liaisons between NPS and the Joint Staff J39. He is the Principal Investigator for multiple research projects with budgets exceeding \$3 million dollars a year, including the TNT, RELIEF, and JIFX projects. <http://faculty.nps.edu/rrbuettner/about.html>

DEPUTY DIRECTOR: Dr. Timothy H. Chung is an Assistant Professor of Systems Engineering at the Naval Postgraduate School. His research interests include probabilistic search optimization, degrees of autonomy for robotic systems, and multi-agent coordination for information gathering applications. His efforts lie at the interface between operations and robotics research. Professor Chung received his doctorate (2007) and M.S. (2002) at the California Institute of Technology in mechanical engineering, specializing in algorithms for distributed sensing and decision-making methods for multi-robot systems. He joined the NPS Operations Research department in 2008, transitioned to the Systems Engineering department in 2011. <http://faculty.nps.edu/thchung/>

DIRECTOR OF STRATEGIC COMMUNICATIONS: Steve Iatrou is a Senior Lecturer in the Information Sciences Department at the Naval Postgraduate School. He is currently the Associate Chair of Distributed Learning, Academic Associate. He received a masters in Systems Technology from the Naval Postgraduate School (1992) and a Bachelors in Journalism and Mass Communication from the University of Oklahoma (1985).

DIRECTOR OF OPERATIONS: Ms. Lisa Trawick has been in the Air Force Reserves for 24 years and is currently serving as a Logistical Readiness Officer for the Surface Deployment and Distribution Command (SDDC). Her previous assignment was a full-time tour for 3.5 years at DFAS Internal Review (IR) as a Financial Data Analyst, where she won the DFAS IR Innovation Award in 2008. In her civilian life she spent 12 years at Frito Lay with various roles in manufacturing/warehouse operations and as a Demand Planner. She received a Bachelors in Statistical Computing from the University of Utah (1998) and a Masters in Information Technology from the Naval Postgraduate School (2008).

DIRECTOR OF CONCEPT GENERATION: Ms. Lyla Englehorn, MPP earned a Master of Public Policy degree from the Panetta Institute at CSU Monterey Bay. She looks at issues related to policy in the maritime domain and is involved in a number of projects at the Naval Postgraduate School. Beyond her work with the Consortium for Robotics and Unmanned System

Education and Research (CRUSER), she also works with the Multimodal Information Sharing Team (MIST), the Operations Research Department, and the NPS Graduate Writing Center. Other work at NPS has included curriculum development and instruction for an International Maritime Security course sequence.

DIRECTOR EMERTIUS/SENIOR ADVISORY COMMITTEE MEMBER: Mr. Jeffrey Kline, CAPT, USN (ret.), is a Professor of Practice in the Operations Research Department at the Navy Postgraduate School and Navy Warfare Development Command Chair of Warfare Innovation. He also is the National Security Institute's Director for Maritime Defense and Security Research Programs. He has over 26 years of extensive naval operational experience including commanding two U.S. Navy ships and serving as Deputy Operations for Commander, Sixth Fleet. In addition to his sea service, Kline spent three years as a Naval Analyst in the Office of the Secretary of Defense. He is a 1992 graduate of the Naval Postgraduate School's Operations Research Program where he earned the Chief of Naval Operations Award for Excellence in Operations Research, and a 1997 distinguished graduate of the National War College. Jeff received his BS in Industrial Engineering from the University of Missouri in 1979. His teaching and research interests are joint campaign analysis and applied analysis in operational planning. His NPS faculty awards include the 2009 American Institute of Aeronautics and Astronautics Homeland Security Award, 2007 Hamming Award for interdisciplinary research, 2007 Wayne E. Meyers Award for Excellence in Systems Engineering Research, and the 2005 Northrop Grumman Award for Excellence in Systems Engineering. He is a member of the Military Operations Research Society and the Institute for Operations Research and Management Science. <http://faculty.nps.edu/jekline/>

LIST OF FIGURES

Figure 1. CRUSER program innovation threads as of September 2014.....	1
Figure 2. Common Operational Environment	9
Figure 3. Student designed CAD rendering of the vehicle.	13
Figure 4. Robot Track Roller	13
Figure 5. Autonomy Algorithm	14
Figure 6. Super exponential growth in big data.....	15
Figure 7. A diverse panel of leading thinkers in the field of ethics and robotic systems, led by NPS Department of Defense Analysis Assistant Professor Dr. Bradley Strawser, shown above center, participates in the Robo-Ethics 2014 event in San Diego CA (24 March 2014).	20
Figure 8. NPS students attending Robo-Ethics 2014 via VTC from the NPS campus in Monterey CA.....	21
Figure 9. The Micro Tactical Ground Robot (MTGR) is piloted along the hull of the Copernicus target vessel in search for a radioactive substance.....	32
Figure 10. Establishing the Boarding Team mesh network to link.....	32
Figure 11. Networked UAV in the starting position before providing aerial images to divers.....	33
Figure 12. Divers on the way to objective and the associated experiment log.	34
Figure 13. UAV taken images transfer to submerged divers.....	35
Figure 14. Problems encountered discussion snapshot.....	35
Figure 15. ROV-Diver networking	36
Figure 16. Errors in estimating underwater glider's trajectory.....	38
Figure 17. Field experiment conducted in the Monterey Bay from January 30, 2014, to February 1, 2014, with 68 dives: (a) experiment area, and (b) trajectories of the Slocum glider.	38
Figure 18. Error reduction ($D2 - D1$) for all the 68 dives of the Slocum glider.	40
Figure 19. The top view of optimally determined (black curve) and dead reckoning determined underwater trajectories for the dive #53.	41
Figure 20: NPS ARSENL field experimentation trailer and ground control station setup (left) and histogram of cumulative sortie counts, with those sorties conducted in FY14 sorties highlighted and showing accelerated development (right).....	43
Figure 21: Customized <i>ZephyrII</i> UAV, Generation E, representing finalized flight systems integration and design (<i>left</i>) and integrated avionics and autonomy payload (<i>right</i>)	43
Figure 22: A team of Systems Engineering students design and build a multi-UAV launcher, based on end-user needs and system requirements (<i>left</i>) and conduct tests of their prototype design (<i>right</i>)	44
Figure 23: A USNR unit member performs a UAV launch (<i>left</i>) and another USNR unit member assists with pre-flight checks (<i>right</i>).....	44
Figure 24: NPS CAVR REMUS 100 with Astronauts (<i>top left</i>) and the Tethered, Hovering Autonomous Underwater System, THAUS, (<i>bottom center</i>) at the Aquarius Habitat (<i>top right</i>)	48

Figure 25. Terrain-Aided Navigation concept (left) and view from REMUS 100 at Aquarius (right).	49
Figure 26. Underwater Garage concept (left), THAUS (right, top), and REMUS 100 with docking station (right, bottom)	51
Figure 27: The Electronics Interface between MISO and CAVR equipment, designed, built, and deployed (<i>top</i>), and the REMUS 100 Docking station deployment at MISO and deployed with a docked vehicle (<i>bottom</i>)	53
Figure 28: Pavlion Lake, BC and under-ice AUV operations at Pavlion Lake	55
Figure 29: Human under-ice operations at Lake Untersee, Antarctica.....	56
Figure 30. InstantEye MR-VTOL unmanned aircraft with radiosonde attached.....	58
Figure 31. InstantEye/Radiosonde alongside.....	59
Figure 32. Block diagram of a WPT system.....	64
Figure 33. Principle and application of inductive power transfer.....	65
Figure 34. Equivalent circuit of the inductive WPT system.....	66
Figure 35. (a) CST MWS model of the WPT coils in air, and (b) simulated efficiency versus load resistance.....	67
Figure 36. Simulation results (b) for coils with ferrite cores and plates (a).	68
Figure 37. Planar array antenna near field model.	69
Figure 38. (a) Plot of normalized electric field in V/m when the array is focused at $z = 2$ m and (b) when the array is focused at $z = 2000$ m. The $1/R$ factor has been removed.....	70
Figure 39: CAD drawing of the prototype Aqua-Quad model including 20-cell solar array, propeller guards, and submersed battery bay.....	71
Figure 40: Motor test stand instrumented by summer intern, Kevin-Patxi Le Bras.	72
Figure 41: Thrust versus RPM for the T-Motor U3 motor with a T-Motor 14 x 4.8 propeller and Castle Creations Talon 35 electronic speed control. Blue circles are data points extracted from the T-motor website. The error-bars indicate a standard deviation for each 30-second run. The few very large errors in RPM are due to a sensing glitch that occasionally shows up in the RPM sensor.....	73
Figure 42: FOM versus thrust for several voltages. See text for the meaning of adjusted measurements. The blue circles represent data points extracted from the manufacturer's website.	74
Figure 43: Estimated target trajectory using 4 drifters with passive acoustic sensors.....	75
Figure 44: Estimated position and velocity errors.	76
Figure 45. Students aboard RV FULMAR recover the NPS Slocum glider during the Tactical Oceanography at-sea laboratory cruise on 04-Aug-2014	77
Figure 46. NPS Spray glider with acoustic receiver deployed near Moss Landing on 12-Aug-2014.....	78
Figure 47. Interim Flight Clearance Process.....	81
Figure 48. NAVAIR IFC Context.....	82
Figure 49. NPS IFC Context.....	82
Figure 50. NRL Jackal UAS	83
Figure 51. BBN Hazard & Risk Analysis Tool	84
Figure 52 Baseline Model (D0P)	88
Figure 53 Integrated Model (D4I).....	89

Figure 54. An NPS Littoral Glider UUV rigged with narwhal mount for acoustic sensor being deployed in Monterey Bay (<i>left panel</i>); an SSC-SD Wave Glider USV with integrated towed acoustic modem being deployed in Hawaii (<i>right panel</i>). ...	91
Figure 55. New science computer for Littoral Glider UUV integrated into electronics bay (<i>left panel</i>); Teledyne-Benthos ATM-903 modem with bulkhead connector sitting atop a block of syntactic foam (<i>right panel</i>).....	92
Figure 56. (a) New METOC sensor mast mounted on NPS Wave Glider Mako. Mako was sitting on the deck of R/V Fulmar before the field deployment on July 30, 2014; (b) Mako deployed in Monterey Bay with the Airmar mast (with an orange flag) and the new NPS METOC mast	95
Figure 57. Intercomparison of wind speed from the WG original sensor (blue), new METOC sensor package, and the MASFlux nearby.....	96
Figure 58. September 2014 Warfare Innovation Workshop, "Warfighting in the Contested Littorals"	98
Figure 59. September 2014 Warfare Innovation Workshop participants	99
Figure 60. CRUSER Technical Continuum (TechCon), April 2014.....	100
Figure 61. CRUSER community of interest growth from January 2011 to July 2014.....	103
Figure 62. CRUSER community of interest breadth of membership, July 2014	103
Figure 63. CRUSER monthly meeting in progress, September 2013.....	104
Figure 64. Robots in the Roses Research Fair, April 2014.....	105

LIST OF TABLES

Table 1. FY14 CRUSER funded projects for curriculum development (alphabetized by Principal Investigator last name).....	8
Table 2. Robo-Ethics 2014 event attendance.....	21
Table 3. FY14 CRUSER mentored NPS student theses (<i>alphabetical by student</i>).....	24
Table 4. CRUSER funded student travel, FY14	28
Table 5. FY14 CRUSER funded projects (alphabetized by Principal Investigator last name)	29
Table 6. Error statistics for D1 (without ocean model) and D2 (with ocean model).....	40
Table 7. Bias and RMS Error Summary*	60
Table 8. Autonomy Degree Summary	86
Table 9. Interdependence Level Summary	86
Table 10. CRUSER Technical Continuum presentations, April 2014 (<i>alphabetical by speaker name</i>).....	100
Table 11. Representative listing of CRUSER program briefings given on request in FY14.	106

ABSTRACT

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems (UxS) in military and naval operations. CRUSER seeks to align efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, and supporting innovation through directed programs of operational experimentation. This FY14 annual report summarizes CRUSER activities in its fourth year of operation, and highlights future plans.

KEYWORDS: robotics, unmanned systems, autonomy, UxS, UAV, USV, UGV, UUV

POC: Dr. Raymond R. Buettner, Jr.,
CRUSER Director

<http://cruser.nps.edu>

LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	anti-access area denial (<i>A2/AD also used</i>)
ACTUV	ASW continuous trail unmanned vessel
AREPS	Advanced Refraction Effects System
ARSENL	Advanced Robotic Systems Engineering Laboratory
ASW	anti-submarine warfare
AUV	Autonomous underwater vehicle
C2	Command and control
C3	Command, control and communications
C4I	Command, control, computers, communications and intelligence
CANSOF	Canadian Special Operations Forces
CAVR	NPS Center for Autonomous Vehicle Research
CENETIX	Center for Network Innovation and Experimentation
CEU	Continuing education unit
CNO	Chief of Naval Operations
COAMPS	<i>U.S. Navy's mesoscale numerical forecast model</i>
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
DoD	Department of Defense
DON	Department of the Navy
DRDC	Defence R&D Canada
EMCON	Emissions controlled
FFI	Norway Defence Research Establishment
FIU	Florida International University

FWG	Germany Federal Armed Forces Underwater Acoustic and Marine Geophysics Research Institute
GCS	Ground control station
HERO	Hazards of electromagnetic radiation to ordnance
IRND	improvised radiological or nuclear device
ISR	Intelligence, surveillance, and reconnaissance
JCA	Joint campaign analysis
JIFX	Joint Interagency Field Exploration
LAR	lethal autonomous robot
LDUUV	large displacement UUV
LiPo	Lithium Polymer
MATE	Marine Advanced Technology Education
MBARI	Monterey Bay Aquarium Research Institute
MDA	Maritime domain awareness
METOC	Meteorological and oceanographic
MILDEC	Military deception
MINDEF	Singapore Ministry of Defense
MIO	Maritime threat detection and interdiction operations
MISSION	Maritime In Situ Sensing Inter-Operable Network
MPPT	Maximum peak power tracker
MvM	Many versus Many
NAVAIR	U.S. Naval Air Systems Command
NAVO	U.S. Naval Oceanographic Office
NAVSEA	U.S. Naval Sea Systems Command
NORSOF	Norwegian Special Operations Forces

NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NUS	National University of Singapore
NUS ARL	National University of Singapore Acoustic Research Laboratory
NUWC	Naval Undersea Warfare Command
NWC	Naval War College
NWDC	Navy Warfare Development Command
ONR	Office of Naval Research
OR	Operations Research Department, NPS
OSD	Optimal spectral decomposition
QR	Quick Response (<i>QR code</i>)
RECES	Robo-Ethics Continuing Education Series
RF	radiofrequency
RLS	recursive least square
ROS	Robot operating system
ROV	Remotely operated vehicle
SEA	Systems Engineering and Analysis (<i>an NPS curriculum</i>)
SECDEF	Secretary of Defense
SECNAV	Secretary of the Navy
SME	Subject matter expert
SOF	U.S. Special Operations Forces
SQMD	squadron manpower documents
SSC Pacific	U.S. Space & Naval Warfare Systems Center
SSG	Strategic Studies Group

STEM	Science, technology, engineering, and mathematics
TaLEUAS	Tactical Long Endurance Unmanned Air System
TDA	Tactical decision aid
TechCon	CRUSER Technical Continuum
TERN	Tactically Exploited Return Node
THAUS	Tethered hovering autonomous underwater system
TNT	Tactical Network Testbed
TRANSEC	Transmissions security
TUAV	Tactical unmanned aerial vehicle
UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
UBS	Unmanned buoy system
UCLASS	Unmanned Carrier Launched Airborne Surveillance and Strike aircraft
UCSC	University of California at Santa Cruz
UGV	Unmanned ground vehicle
USMC	U.S. Marine Corps
USN	U.S. Navy
USNA	U.S. Naval Academy
USV	Unmanned surface vehicle
USW	Undersea Warfare (<i>a battle concept and an NPS curriculum</i>)
UUV	Unmanned undersea vehicle
UxS	Unmanned system
WIW	Warfare Innovation Workshop

ACKNOWLEDGMENTS

The CRUSER Director thanks the entire community of interest who joined us since the program inception in March 2011 – we look forward to many successful years to come.

The CRUSER Director acknowledges the continued contributions of the CRUSER Deputy Director, Dr. Timothy H. Chung.

The CRUSER Director appreciates the support and guidance of former Under Secretary of the Navy Robert Work, and we wish him luck in his future efforts.

The current CRUSER Director owes thanks for all program successes to the extraordinary work of the first CRUSER Director, CAPT Jeff Kline, USN (ret.)