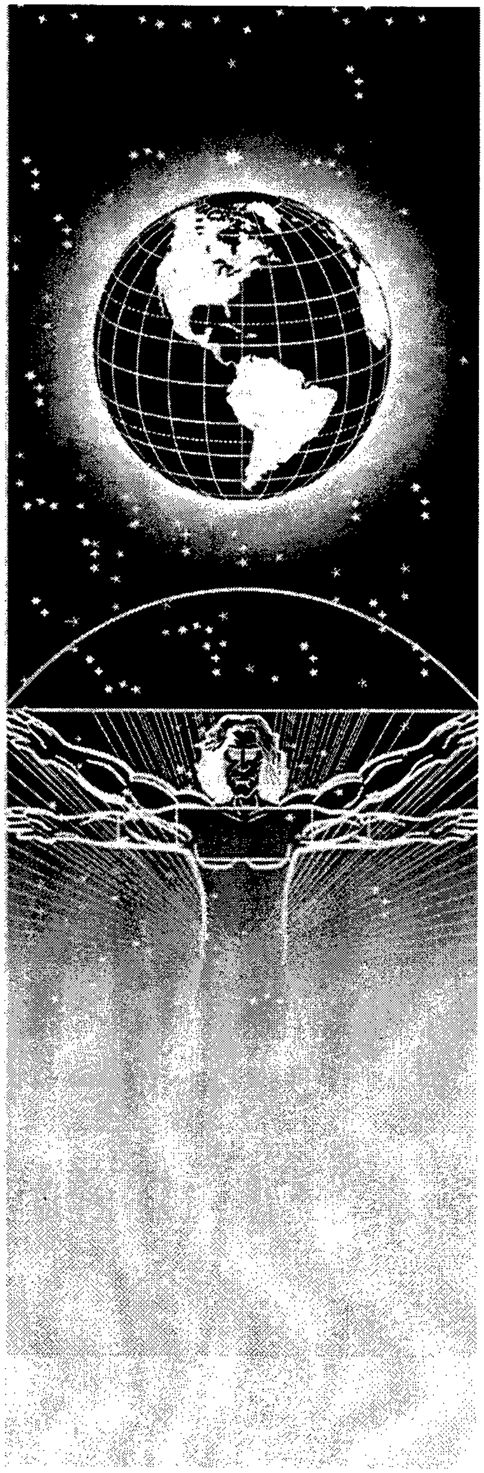
AFRL-HE-WP-TR-1998-0013



UNITED STATES AIR FORCE RESEARCH LABORATORY

SEAD AND THE UCAV: A PRELIMINARY COGNITIVE SYSTEMS ANALYSIS

John M. Flach

LOGICON TECHNICAL SERVICES, INC.
P.O. BOX 317258
DAYTON OH 45437-7258

WRIGHT STATE UNIVERSITY
3640 COLONEL GLENN HIGHWAY
FAIRBORN OH 45324

Robert G. Eggleston
Gilbert G. Kuperman
Cynthia O. Dominguez

HUMAN EFFECTIVENESS DIRECTORATE
CREW SYSTEM INTERFACE DIVISION
WRIGHT-PATTERSON AFB OH 45433-7022

FEBRUARY1998

INTERIM REPORT FOR THE PERIOD MAY 1997 TO FEBRUARY 1998

Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB OH 45433-7022

NOTICES

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-1998-0013

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Hendrick W Ruck

HENDRICK W. RUCK, PhD
Chief, Crew System Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1998

3. REPORT TYPE AND DATES COVERED
Interim Report for 21 May 1997-28 February 1998

4. TITLE AND SUBTITLE
SEAD and the UCAV: A Preliminary Cognitive Systems Analysis

5. FUNDING NUMBERS
C: F41624-94-D-6000
PE: 62202F
PR: 7184
TA: 10
WU: 45

6. AUTHOR(S)
*John M. Flach, Robert G. Eggleston, Gilbert G. Kuperman, Cynthia O. Dominguez

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Logicon Technical Services, Inc.
P.O. Box 317258
Dayton OH 45437-7258

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-HE-WP-TR-1998-0013

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFRL), Human Effectiveness Directorate
Crew System Interface Division
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7022

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*Wright State University
3640 Colonel Glenn Highway
Fairborn OH 45324

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report is the first step of a program with three explicit goals: (1) to illustrate and test the framework of Cognitive Systems Engineering (CSE) for use in military systems analysis and design; (2) to generate a database that will be useful for designers and managers working on the development of UCAVs for use in the SEAD mission; and (3) to develop interfaces for UCAVs. These goals are tightly coupled in that the usefulness of the database and the ability to develop effective interfaces and user-aiding concepts will be the true test of the CSE framework. The report is most relevant to the second goal. It provides a CSE framework for interpreting and organizing data generated from cognitive task analyses of the SEAD mission. The CSE framework is unique in that it develops a holistic approach to human-socio-technical systems. It explicitly considers factors in design analysis that go beyond the technology boundaries of a system to reveal important constraints for proper consideration in the process of synthesizing a design concept. The report illustrates initial benefits of this form of system analysis.

14. SUBJECT TERMS
suppression of enemy air defense, uninhabited aerial vehicle, cognitive engineering, systems design, systems analysis, user interface design, work domain modeling

15. NUMBER OF PAGES
56

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

This page intentionally left blank.

PREFACE

This project evolved from a desire to produce an integrated "living" data base that could be used to support decision makers throughout the life cycle of a complex military system. It represents a first step in achieving this goal. The underlying belief is that the quality of design and operational decisions will improve in relation to one's ability to discern and understand the underlying constraints of the work domain in which the system will operate. Constraints come in many forms and from many different sources: physical, physiological, organizational, social, political. Many constraints evolve and change over time as a system is conceived, designed, and fielded; hence the need for a living data base. We believe decision makers need a common foundation from which they can be *guided by essential constraints* while they make decisions that *impose new constraints* in system design and use. We speculate that essential constraints are closely connected to the nature of the work and the environmental context in which it is accomplished. However, it is a difficult task to discern and separate "essential" constraints from incidental ones. It is not easy to determine if a constraint is a consequence of old technology, a characteristic of the job problem, or based on a multitude of socio-technical interactions. It is not easy to discover universal principles that can be used to establish primacy among constraints. The research summarized in this report represents our initial attempt to ferret out essential constraints for the development of an uninhabited combat aerial vehicle (UCAV), and to elucidate a framework that can be used both to guide the search for constraints and as a method that can be used to systematically represent them at different levels of abstraction. Each representation shows how the constraint becomes instantiated in design and operational decisions. In this way it both guides decision makers and serves as a tool to capture the consequences of their own decisions.

This work was accomplished in support of Task 718410, Multi-Operator Systems Aiding. The project manager was Robert Eggleston of AFRL/HECI. The principal investigator for the project was John Flach working under subcontract to Logicon Technical Services, Inc., Dayton, Ohio.

We wish to acknowledge the generous assistance provided by our colleagues and co-workers. We are deeply indebted to Jens Rasmussen. His work provides the intellectual foundation from which our efforts have been derived. In addition, Jens has provided many helpful comments throughout this project and has graciously shared preliminary drafts of his latest work on UCAVs. We also wish to express our appreciation to Paul Jacques for sharing his knowledge as an EWO; to Valerie Shalin for sharing her early work to develop goal plan graphs to describe the information processing of the EWO; to Tom Hughes for providing useful feedback on early drafts of this report; and to all three for providing pointers to useful data sources. Finally, we thank Anne Cato for her general assistance, especially her diligent work in solving cross-platform issues associated with format editing.

EXECUTIVE SUMMARY

This report considers the design of UCAVs for use in SEAD missions within the framework of Cognitive Systems Engineering (CSE). The CSE framework has been developed as a holistic approach to human-socio-technical systems. A critical objective of the CSE approach is to make the significant features of a workspace (e.g., the SEAD mission) explicit. These significant features reflect both how the system might work (causal constraints) and why it is desirable for the system to work (functional constraints) a certain way. This explicit representation of the demands of the problem space might then inform the design and application of technologies (e.g., UCAVs) and the coupling of these technologies with human operators to reduce cognitive complexity and to increase efficiency and reliability in achieving the functional objectives for the system. This report summarizes preliminary results from a tabletop analysis of the SEAD mission and of available UCAV technologies. The emphasis is on understanding the situation constraints on performance.

This report is the first step of a program with three explicit goals. The first goal is to illustrate and test the CSE framework. The second goal is to generate a database that will be useful for designers and managers working on the development of UCAVs for use in the SEAD mission. The third goal is to develop interfaces for UCAVs. These goals are tightly coupled in that the usefulness of the database and the ability to develop effective interfaces will be the true test of the CSE framework. This report is most relevant to the second goal. The structure of the report provides a preliminary framework for structuring data generated from cognitive task analyses of the SEAD mission. This data will be organized to reflect functional (i.e., means-ends) constraints at different levels of abstraction and levels of decomposition with respect to part-whole relations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page intentionally left blank.

I. INTRODUCTION

"Build and evaluate a UAV for the SEAD mission as an early application of UAVs in a cued attack role"

"Increase emphasis on the development of effective human-system integration techniques for flight management and employment of unmanned air vehicles"

Worch (1997)

This report is a preliminary attempt to address the above recommendations from the Air Force Scientific Advisory Board's report on UAV Technologies and Combat Operations (Worch, Borky, Gabriel, Heiser, Swalm, & Wong, 1996). The focus is on the *use* of uninhabited air vehicles for suppression of enemy air defenses (SEAD). This report outlines an approach based on Rasmussen's framework for Cognitive Systems Engineering (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994) and illustrates the approach in the context of a localized SEAD mission.

The introduction will provide some background on the SEAD mission, UAVs, and Cognitive Systems Engineering (CSE). The later sections will provide more in-depth analyses of the SEAD mission. These analyses are primarily based on a search of archival records on the SEAD mission, on electronic warfare, and on UAVs. As such, it is only a first step. However, we think that it is a positive first step that will lay the groundwork for more thorough cognitive task analyses. The goal of CSE is to develop integrated interfaces and user-aiding subsystems to support human operators so that they can be responsive to the meaningful properties of work situations; and thus, perform as effective controllers and problem solvers (Also see Rasmussen, 1998 for related discussions).

I.A. SEAD

"Suppression of enemy air defenses (SEAD) is any activity that neutralizes, destroys, or temporarily degrades enemy surface-based defenses by destructive and/or disruptive means" (Joint Pub 3-01.4, 1995). The SEAD mission is in the process of evolution. This evolution reflects the changing technology of both surface-based defense systems and the technology available for attacking these systems.

The beginnings of the SEAD mission can be traced to the first uses of aircraft (i.e., balloons) in the American Civil War and the Franco Prussian War. From that time on there has been a duel for control of the third dimension between those on the ground and those in the air. The combination of physical and electronic measures, counter-measures, and counter-counter-measures that characterize the modern SEAD mission evolved as a response to the SA-2 SAM (surface to air missile) threat that arose during the Vietnam War:

Aircrews had dealt with threats --- fighters and antiaircraft artillery (AAA) --- since the beginnings of the use of aircraft in combat, but the introduction of the Soviet-built SA-2 surface-to-air missile (SAM) ushered a new and deadly threat into an air war over Vietnam. Although the SA-2 was not an unexpected threat --- having earlier shot down two American U-2 reconnaissance aircraft --- the US Air Force's tactical forces were largely unprepared. (Hewitt, 1993)

The SAM threat was countered by the development of the Wild Weasel --- an aircraft (recently an F-4G, more currently an F-16 block 50 series) configured with electronics for detecting and homing on radar emissions from SAM sites (for the F-16 this is the HARM Targeting System --- HTS). The SEAD mission was an extremely dangerous mission since the airframe and aircrew were often required to operate within range of the surface threats that they were trying to suppress. The SEAD aircraft tried to fly close enough so that the enemy would turn on the targeting radar, but not close enough for them to take a high probability shot. This was referred to as "stimulating the environment." This was a dangerous game, particularly, when there were unknown threats in the area of engagement.

In many respects, the approach to SAMs in Vietnam was "piecemeal" (Brungess, 1994). The integrated air defense system (IADS) developed by the North Vietnamese, however, was not a simple collection of SAMs, but a highly integrated system. Brungess (1994) describes this system:

During the technological chess game between the US and the Soviet-equipped North Vietnamese, a qualitative change took place in the North Vietnamese IADS that the US was slow to recognize. The strategy of air deniability in mid-1968 included 250 ground controlled interceptors (GCI), 1,500 radar-directed and optical AAA sites, and over 300 SAM sites netted together by a centrally controlled and directed integrated structure. A sophisticated early-warning radar net consisting of the latest Soviet radars, communications apparatus, passive detection nets, and intelligence-gathering agencies fed an increasingly integrated air defense network. From the North Vietnamese view, the IADS was an indivisible organization composed of interdependent, interlocking parts comprising a complete "nervous system" and associated striking "muscle" (p. 8).

Table I.: SEAD in the Gulf War (from Brungess, 1994)

Threat	Most formidable faced by American military based on capability, numbers, command and control structure and modernization. Countrywide radar-warning net consists of multiple Western-designed and Soviet radar systems tied together with redundant and hardened command, control, and communications (C^3) net. Advanced computer technology employed in target tracking, weapons allocation, and sector control. Iraqi air force, AAA, and SAM systems fully integrated. Frontline personnel well trained, secondary back-up echelon poorly trained. Doctrinally tied to "weapons close-hold" use; poor discipline results in random, wasteful use of weapons.
Defini-tion	Campaign-based SEAD. Use of all aircraft to execute SEAD campaign. Difference between way campaign was defined and way it was executed. Definition separated offensive counter air (air-to-air) and SEAD (suppression of radars). Executed as single, coordinated IADS attack plan. Distinction drawn between tactical and strategic SEAD. Tactical SEAD related to day-to-day suppression of battlefield operations against Iraqi field army. Strategic SEAD directed at degradation of overall Iraqi IADS.
Tactics	Full spectrum, Electronic combat-based tactical deception, integrated use of EF-111/EA-6, HARM shooters (F-4G, F-16C, Navy aircraft). Near real-time relay of critical electronic combat data coordinated through AWACS, E-3, RC/EC-135, E-2C, prototype JSTARS. Neo-Iron Hand tactics against known sites using combination of jamming, ARMs, standoff ordinance (glide bombs, Mavericks, Hellfire missiles, cluster bomb units, or general-purpose bombs).
Organi-zation	Centralized control, decentralized execution. Strategy, general battle plan tactics developed by joint coalition staff. Specific elements of plan tasked to specific units. Developed as war-planning organization as opposed to raid or campaign of Libya or Bekka Valley operations. Heavily dependent on reliable, efficient communications among forces to make organization viable.
Force Structure	Very heavy emphasis (above 50% of force) dedicated to SEAD effort during initial phases. Actual percentage of SEAD-specific assets very small (EF-111s, EA-6s, F-4Gs, EC-130Hs accounted for less than 3% of total air forces). Specialization of SEAD assets diminished, emphasis on object of SEAD campaign with whatever assets could perform task.
Strategy	Highly evolved SEAD strategy. Multileveled from strategic to tactical, from specialized function to general campaign. Integrated with doctrine. Plan: destabilize the Iraqi IADS and keep it destabilized. Neutralize those portions that pose a threat to attackers, deny their IADS the use of electromagnetic spectrum, while exploiting other elements of the spectrum for deception and intelligence-gathering purposes. An extended use of Libyan raid mentality. By relentlessly keeping pressure on IADS through jamming, ARMs, selected Iron Hand attacks, seized the initiative by maximizing confusion. Instead of 11 minutes of confusion, there were six weeks. The intentional shaping of the electronic battlefield. A use of air-land battle concept extended in three dimensions and encompassing the use of the electromagnetic spectrum. Variation of Navy's "electronic combat rollback" emphasizing versatile use of aircraft in executing SEAD. Based on striking first, prepared to repel attack if it came and retake initiative.
Doctrine	AFM 1-1, 16 Mar 84, in force during the Gulf War. SEAD subsumed as element of counter air, and also element of electronic combat. Joint doctrine separated JSEAD from C^3CM, and subsumed electronic warfare under C^3CM. Desert Storm combined elements of both in strategic/tactical applications.
Tech-nology	Very sophisticated technology used by both sides. Technology fairly evenly matched. SAMs employed latest Soviet/Western guidance techniques and electronic counter-countermeasure advances. Fiber optics, highly directional microwave communication net, state of the art. Iraqi fighters practiced fully coordinated night GCI operations using latest Soviet and French fighters and air-to-air missiles. Technology too sophisticated to tackle immediately; months-long preparation required, in some cases, to design specific counters. US use of digitally reprogrammable equipment critical to success of adapting to rapid changes in Iraqi use of electromagnetic spectrum (i.e., rapid response to "war modes:) , especially for HARMs and radar warning receivers.
Political	Strong support throughout. Well-orchestrated coalition to acquire needed authority to use armed force. Unspoken objectives politically motivated; minimum US casualties, rapid moving war with clearly visible, continued success terminating in unconditional, unambiguous military victory. Political objective to "stabilize regional relationship" unclear in pragmatic terms. Possible result: reintroduction of armed force to region at later time. National interest defined in economic and altruistic terms: "free Kuwait" and "Protect the oil resource" used interchangeably.

IADS have continued to evolve and the SEAD mission has had to evolve in response. Brungess (1994) traces this evolution through Vietnam, the Israeli-Syrian conflict in the Bekka Valley, Libya, and Desert Storm. The SEAD mission has evolved from a piecemeal approach in which specific SAMs are attacked in support of local objectives to a full "integration of total-force structures in the achievement of total-force objectives. SEAD has started to become JSEAD" (Burgess, p. 42; J - Joint SEAD). Table I., adapted from Brungess (1994, p. 43 - 44), gives a summary of key trends reflected in the Gulf War.

The SEAD mission is evolving in response to increasingly sophisticated IADS and to take advantage of advanced technologies. However, the evolution is not simply being driven by technology, but also by political (e.g., minimize US casualties) and economic (e.g., "do more with less") forces. These forces are an important reason why the Air Force is currently considering UCAVs as a potential technology to employ as part of the SEAD mission.

I.B. UCAV

Uninhabited combat aerial vehicles (UCAVs) represent a new operational concept for the Air Force. Uninhabited aerial vehicles have been used extensively by the Israeli Air Force and Pioneer UAVs were employed with great success during the Gulf War. The Israeli's used Samson drones to deceive the Syrian radars in the Bekka Valley. The Samson can mimic the radar cross section (RCS) of an attacking aircraft. By drawing enemy fire the drones created openings for manned aircraft to attack the Syrian IADS. The primary missions for the Pioneer during the Gulf War were for reconnaissance (including identification of targets and battle damage assessment). The idea of using remotely piloted vehicles as a platform for weapons, however, is a new operational concept.

Currently, the Air Force has three UAV Programs --- Predator, Global Hawk, and Dark Star. Table II lists some general information about each of these platforms and Table III provides information about the sensors and communication systems.

Table II: General Characteristics of UAVs

Characteristics	Predator (MAE UAV)	Global Hawk (CONV HAE UAV)	DarkStar (LO HAE UAV)
Altitude:			
Maximum	7.6 km, 25,000 ft	19.8 km, 65,000 ft	>15.3 km, >50,000 ft
Operating	4.6 km, 15,000 ft	15.2-19.8 km 50,000-65,000 ft	>15.3 km, >50,000 ft
Endurance (max)	>30 hrs	>38 hrs	>8 hrs
Radius of Action	926 km, 400 nm	5,556 km, 3,000 nm	>926 km, >500 nm
Speed:			
Max	204-215 km/hr 110-115 kts	>639 km/hr > 345 kts	>523 km/hr >300 kts
Loiter	120-130 km/hr 65-70 kts	639 km/hr 345 kts	>523 km/hr >300 kts
Cruise	111-120 km/hr 60-65 kts	630 km/hr 340 kts	>523 km/hr >300 kts
Climb Rate (max)	168 m/min, 550 fpm	1.036m/min,3,400fpm	610m/min, 2,000 fpm
Propulsion (engines)	1 Fuel-Inj Rec; 4stroke	One Turbofan	One Turbofan
Maker	Rotax 912/Rotax 914	Allison AE3007H	Williams FJ 44-1A
Rating	63.4/75.8kw 85/105hp	32 kN 7,050 lb stat thr	8,45 kN 1,900 lb st thr
Fuel	AVGAS (100 Octane)	Heavy Fuel (JP-8)	Heavy Fuel (JP-8)
Capacity	409 L, 108 gal	8,176 L, 2,160 gal	1,575 L, 416 gal
Weight:			
Empty	544 kg, 1,200 lb	4,055 kg, 8940 lb	1,978 kg, 4,360 lb
Fuel Weight	285 kg, 650 lb	6,668 kg, 14,700 lb	1,470 kg, 3,240 lb
Payload	204 kg, 450 lb	889 kg, 1,960 lb	454 kg, 1,000 lb
Max Takeoff	1, 043 kg, 2,300 lb	11,612 kg, 25,600 lb	3,901 kg, 8,600 lb
Dimensions:			
Wingspan	14.8 m, 48.7 ft	35.4 m, 116.2 ft	21.0 m, 69 ft
Length	8.1 m, 26.7 ft	13.5 m, 44.4 ft	4.6 m, 15 ft
Height	2.2 m, 7.3 ft	4.6 m, 15.2 ft	1.5 m, 5 ft
Avionics:			
Transponder	Mode IIIC IFF	ModeI/II/IIIC/IVIFF	Mode IIIC IFFF
Navigation	GPS and INS	GPS and INS	GPS and INS
Launch & Recovery	Runway (2,500 ft)	Runway (5,000 ft)	Runway (<4,000 ft)
Guidance & Control	Prepgmd/remote/ autonomous	Prepgmd/autonomous	Prepgmd/autonomous

I.B.1. Predator

The *Predator* is currently deployed in Bosnia in support of the Dayton Peace Accords. It is a medium altitude endurance (MAE) UAV and is primarily utilized in a surveillance role including combat assessment, enemy offensive/defensive position monitoring, and camouflage, concealment, and deception identification. Its payload includes electro-optical (EO) sensors capable of providing real-time battlefield television quality images in daylight fair-weather conditions; infrared (IR) sensors that provide real-time monochrome images of emitted heat energy in the mid-infrared band; and Tactical Endurance Synthetic Aperture Radar (TESAR) that provides near-real-time images of sufficient resolution to detect and recognize equipment types present in the scene such as tanks, trucks, or tactical aircraft. The Predator operational concept supports dynamic retasking where supported tactical units can request immediate changes in coverage area and times to reflect changing intelligence requirements. The Predator's deployment package includes three or four air vehicles, a ground control station, a Trojan SPIRIT II communications suite, and approximately 55 people. The people include air vehicle operators, who are qualified pilots; payload operators, who are qualified imagery analysts; and maintenance technicians, and supporting squadron administration personnel.

Table III: Sensors and Communications

[illegible]	[illegible]	[illegible]
Sensors	**EO, IR, and SAR**	**EO, IR, and SAR**
Data Links		
Type	**C-band/LOS; MILSATCOM; Ku-band/SATCOM**	**Ku-band/SATCOM; X-band CDL/LOS UHF/MILSATCOM**
Bandwidth	**C-band/LOS: 20 Mhz SATCOM Ku-band: 5Mhz**	**SATCOM UHF: 25 kHz Ku-band: 2.2-72 Mhz X-band CDL/LOS: 10-120 Mhz**
Data Rate	**C-band/LOS: Analog SATCOM UHF: 4.8 kbps Ku-band: 1.544 Mbps**	**SATCOM UHF: 19.2 kbps Ku-band: 1.5-50 Mbps X-band CDL/LOS: 274 Mbps**
C2 Links	**MILSATCOM**	**UHF/MILSATCOM: Ku-band/SATCOM; UHF/LOS; X-band CDL/LOS**

I.B.2. Global Hawk

The *Global Hawk* is a conventional high altitude endurance (CONV HAE) UAV. This platform is currently in a test stage of development. It is envisioned as a platform that will be capable of loitering in an operation area at high altitude (65,000 ft) for extended durations (24 hour loiter). It is being designed to be capable of monitoring all movements over an entire battle area (40,000 NM^2). It will be designed to search large areas at high resolution and small areas at very high resolution. It will also be capable of providing continual surveillance of small areas. The Global Hawk ground control segment includes a Launch and Recovery Element (LRE) and a Mission Control Element (MCE). The MCE is designed for four operators and its functions include communications, command and control, mission planning, and quality control image. The LRE is designed for two operators. The Global Hawk allows the mission control element to override heading, altitude, and airspeed. The mission control element can initiate pre-planned patterns or command specific profiles. The latency in the control communication links is on the order of seconds.

I.B.3. Dark Star

The *Dark Star* is a low observable high altitude endurance (LO HAE) UAV. It is designed for less capability for surveillance but for higher survivability (i.e., greater stealth) than the Global Hawk. Dark Star will soon be back in a test phase of development. The first model crashed due to a stall on take-off. The Dark Star is designed to utilize the same two-element ground control segment as the Global Hawk. The Dark Star will be waypoint driven. That is, there will be no direct control of altitude, heading, or airspeed. It will be designed to allow quick selection of alternative takeoff, landing, and flight profiles using a mission planner. Both the Dark Star and Global Hawk have take-off abort, landing wave-off, and in-flight pre-programmed contingency profiles that can be selected from the ground control.

I.B.4. UCAV. Concept

The UCAV is currently in the conceptual development phase. None of these planes are flying (at least not in unclassified programs). However, numerous major defense contractors are working on the concept. Sweetman (1997) describes a Lockheed Martin concept as "a flying wing, shaped like a diamond when viewed from above; it is small enough to be carried to the war zone inside a C-5 or C-17 transport" (p. 99). To enhance stealth, this light and efficient vehicle will cruise "into the target area upside down, concealing the engine inlet and the landing gear and weapon-bay doors from radar" (Sweetman, 1997).

The Lockheed Martin UCAV will be designed to be controlled from aircraft flying safely beyond the enemy ground based integrated air defense systems. Feedback to this operator will be provided by surveillance radar and real-time video from the UCAV. Because the UCAV is anticipated to be able to approach within 5-miles of targets, small weapons with simple guidance systems are being considered. These weapons will be low weight and the point-attack warheads will reduce potential risks for collateral damage.

I.C. Cognitive Systems Engineering

An alternative translation for the UCAV acronym might be:

Underspecified
Collaborative
Adaptive
Vulnerable

Underspecified refers to the fact that the utilization of UAVs for combat, (i.e., as weapon platforms) is a novel use of the technology for which only preliminary, vague concepts of operation exist. This represents a unique opportunity for CSE to participate in the design of the operational concepts from the ground up; as opposed to being brought in post hoc in response to catastrophic failures linked to human error.

Vulnerable refers to the fact that, because the UCAV technology is novel, there is low tolerance for failure. An early catastrophic failure (e.g., fratricide) could scuttle the whole concept. If the system is not designed right the first time, there might not be another opportunity. Designing the system right will not be possible without a broad framework that carefully considers both the functional roles for humans and machines.

The collaborative and adaptive nature of the UCAV/SEAD mission is what makes this an interesting and challenging application for CSE. The next two subsections will elaborate on these two dimensions of the problem.

I.C.1. Collaborative System

The UCAV is a *collaborative* system in that it will involve coordination among multiple intelligent agents. These agents include both human operators and machine agents (e.g., automatic control and other support systems). The particular configuration of operators and automatic control systems is an example of what Sheridan (1997) would call a multiple task telerobotics control system. "Multiple" refers to the goal to have a single operator control several UAVs (4 - 6). "Tele-" refers to the fact that the operator will be located in a remote location relative to the workspace. The operator will interact with a local computer through displays and controls. The local computer will, in turn, communicate with another computer co-located in the remote workspace with the "robot." "Robotic" refers to the fact that the controlled process (e.g., UCAV) has its own computer and has a capability for autonomous action.

The remoteness of the operator relative to the battle and the autonomous capability of the UCAV are principal challenges relative to effective collaboration (and thus unique challenges for design). The remoteness means that the operator is dependent on the displays as the primary (if not sole) source of information about system operation. What information is necessary, useful, sufficient? How should this information be configured so that the operators can quickly and accurately assess the situation and gauge the relative appropriateness of response alternatives?

The autonomous capability of the UCAV raises questions about authority (who's in charge?); about responsibility (who does what, when?); about intentionality (why did it do that?); and about trust (will it do the right thing?). Advances in technology make these questions very difficult to answer. The pat answers that the human is always in charge or the allocation of responsibility according to Fitts' (1962) list of what human's do better and what machines do better are no longer adequate (Eggleston, 1987; 1988). The distinctions between the abilities of humans and of machines get fuzzier every minute (Eggleston, 1993). Also, fixed, hierarchical authority structures tend to be brittle and prone to coordination failure due to the fact that there is an information gap between the sharp end of the system and any centralized authority. The sharp end of the system needs to have more autonomy to deal effectively with dynamically changing workload and to fully utilize distributed information (See Rochlin, LaPorte, and Roberts' 1987 analysis of shifting authority during landing on an aircraft carrier. See also Whitaker & Kuperman's 1996 analysis of an attack against time critical targets.)

The need to reveal the underlying rationality of actions (why did it do that?) and to build trust between the human and automated agents places added burden on the interface that now must provide information not only about the outcomes of decisions, but also about the process rationality driving those outcomes (Eggleston, 1988). Thus, the issue becomes *how to design the automated components (e.g., automation and interfaces) to be effective team players within a distributed collaborative control system* (e.g., Woods, Johannesen, Cook, & Sarter, 1994).

I.C.2. Adaptive Systems

The UCAV is an example of an *adaptive* system because it needs to function in a nondeterministic, dynamically changing environment. Combat is not a static encounter, but a dynamic interaction between two competing agents. The environment that exists when a mission is planned may be vastly different from the environment at the time of mission execution. Plans must be monitored, updated, revised, and/or discarded in response to a dynamically changing context. To gain maximal advantage over the enemy, it is important to have the capability to dynamically retask in the light of the latest intelligence.

The need to be adaptive to dynamically changing events is another design challenge. The interface must not only provide an effective representation for predictable events, but must also help the operator to adapt to unexpected events. How do you design for the unexpected? This requires a perspective that considers the widest range of possible events. To deal with unexpected events, CSE tends to focus on constraints or boundary conditions, rather than on events or activities. The challenge for designing adaptive cognitive systems is to *effectively leverage the intelligence, intuition, and* *creativity of the human operators to deal with the unpredictability and "normal accidents" (Perrow, 1984) that can be expected in complex socio-technical systems.*

I.C.3. UCAV and Cognitive Systems

Rasmussen's CSE framework is uniquely suited to the collaborative, adaptive requirements of the SEAD mission. Figure I.adapted from Rasmussen illustrates the scope of a cognitive task analysis that assesses both operator independent constraints inherent in the "situation" and operator (and social context) dependent constraints that limit "awareness." A complete cognitive task analysis must consider both situation constraints and awareness constraints. However, the situation constraints will take precedence in our analyses. This is because the situation constraints are seen as the givens for the design problem. In this sense, they represent the problem to be solved.

The awareness constraints, on the other hand, are far more dependent on design decisions. That is, the awareness constraints will be dependent on function allocation and interface design. In this sense, *the cognitive engineering problem is to shape the constraints on awareness (e.g., by design of the automation, the interfaces, and allocation of functions) so that they meet the demands created by the situation.* The human operators are not considered the weak link in the system, but a critical resource for designing a stable and reliable distributed, adaptive collaborative control system. The challenge is to utilize the adaptive capacity of the human operators as effectively as possible. Thus, this report will focus on the demands of the SEAD situation illustrated in the top half of Figure I.

The diagram in Figure I. shows the two sides of the cognitive engineering problem. On the one hand, the situation provides the foundation for a normative approach to meaning. That is, this half of the cognitive systems equation addresses meaning in terms of significant attributes of the workspace in terms of means and ends. What are the functional goals and the physical, resource, and control constraints to achieving those goals. This side of the equation reflects the demands created by the work. It represents the problem space. On the other hand, the awareness side of the equation, addresses constraints arising from cognitive or computational processes. Here the focus is on organizational and cognitive constraints/resources that are available to perceive, interpret, and respond to meaningful properties of problems. Performance depends on a good match between situation demands and awareness resources. That, again, is the goal of cognitive systems analysis, to uncover mismatches between work demands and cognitive resources. Once these mismatches are uncovered the CSE problem is to design integrated interfaces, problem solving and collaborative support aids, and training protocols that bridge the gap between demands and resources --- so that the cognitive agents' awareness is consistent with the situation.

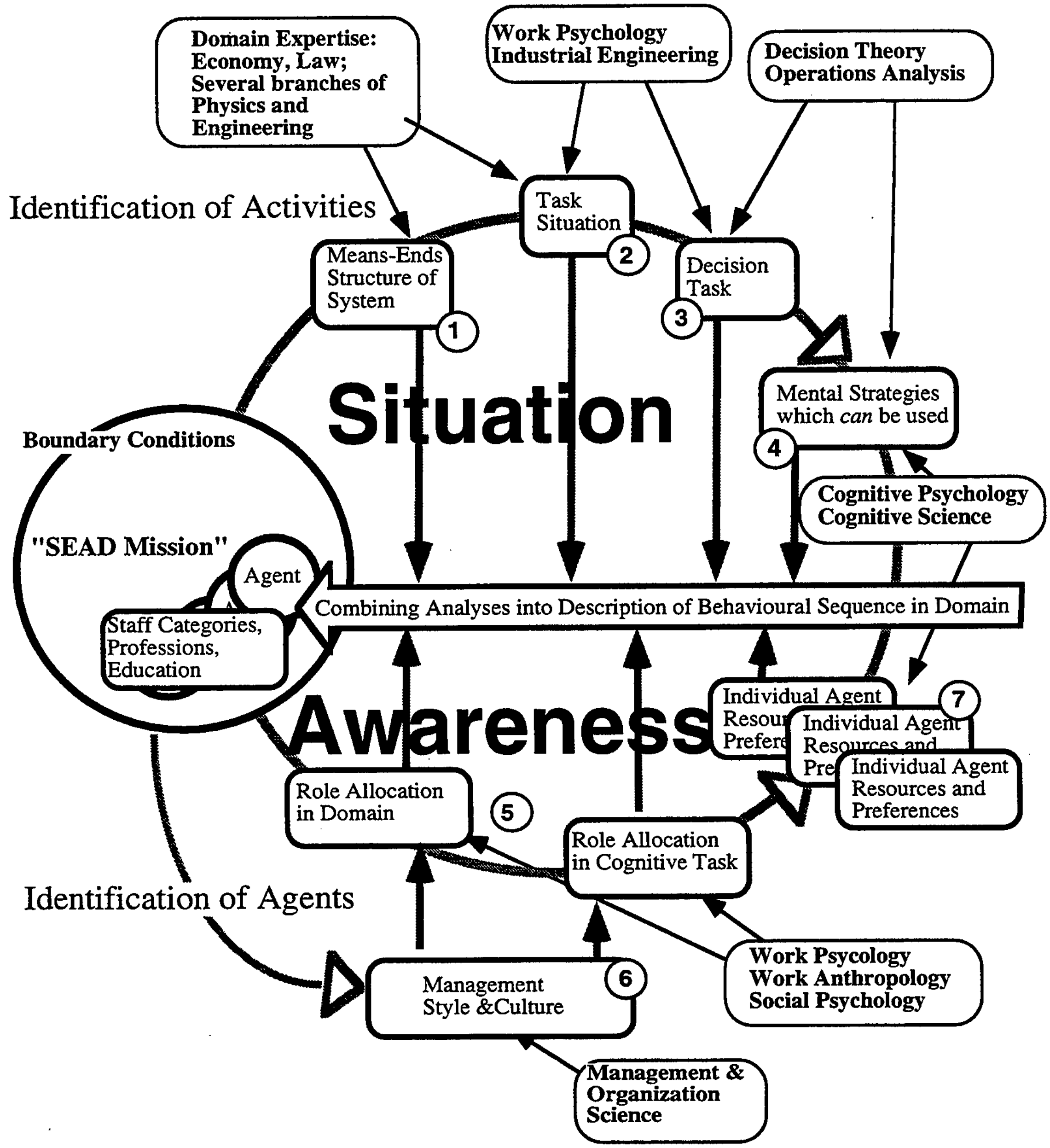


Figure I. This diagram illustrates how multiple perspectives contribute to a complete understanding of a work domain in terms of constraints on the work situation and constraints on awareness.

In characterizing the demands of a workspace, Rasmussen has found it useful to orient the analyses with respect to two dimensions: abstraction and level of decomposition. Rasmussen (1986) has distinguished five different levels for characterizing complex socio-technical systems with respect to the abstraction dimension. Brief descriptions are presented here, however, these levels will be more fully explicated in later sections of this report:

Functional Purpose. This level identifies the goals and values of the work domain. What is the purpose of the system and what are the figures of merit for gauging the success of the system?

Abstract Function. This level specifies the problem domain in terms of abstract dimensions that bridge between the values reflected at the level of functional purpose and the physical constraints that bound the flow of activities and the operation of technologies to support those goals.

General Function. This level decomposes the system into processing units with identifiable inputs and outputs. Each processing unit is characterized in terms of a transfer function that translates inputs to outputs.

Physical Function. This level identifies the types of technology (e.g., human operator, computer, hydraulic or mechanical system, etc.) which is associated with each of the functions.

Physical Form. This level provides a detailed accounting of the space/time properties of the system (e.g., where things are located, what's connected to what, etc.) and of system performance (e.g., what happens, when).

Each level of abstraction refers to qualitatively different categories of constraints that contribute to the situation. These qualitatively different categories are related in a nested hierarchy structure. Categories at higher levels within this hierarchy provide the rational context for understanding why lower level constraints are significant. Categories at lower levels in the hierarchy provide the physical details of how constraints at higher levels can be implemented. The nested hierarchy is typically represented as a triangle (Figure II). This graphic reflects the intuition that relatively few categories are needed to meaningfully characterize high level constraint of the work domain. However, for lower levels many more categories and distinctions are relevant to a meaningful characterization. This difference in level of decomposition reflects the second dimension of analysis --- part-whole decomposition. Together these dimensions can be crossed to create a two dimensional space for characterizing the analysis process. As a result of work in many different work domains and after analyzing many verbal protocols of domain experts, Rasmussen found that experts tend to reason along the diagonal of this analysis space. That is, expert reasoning tends to move from global descriptions of functional goals to detailed specifications of particular actions on specific components.

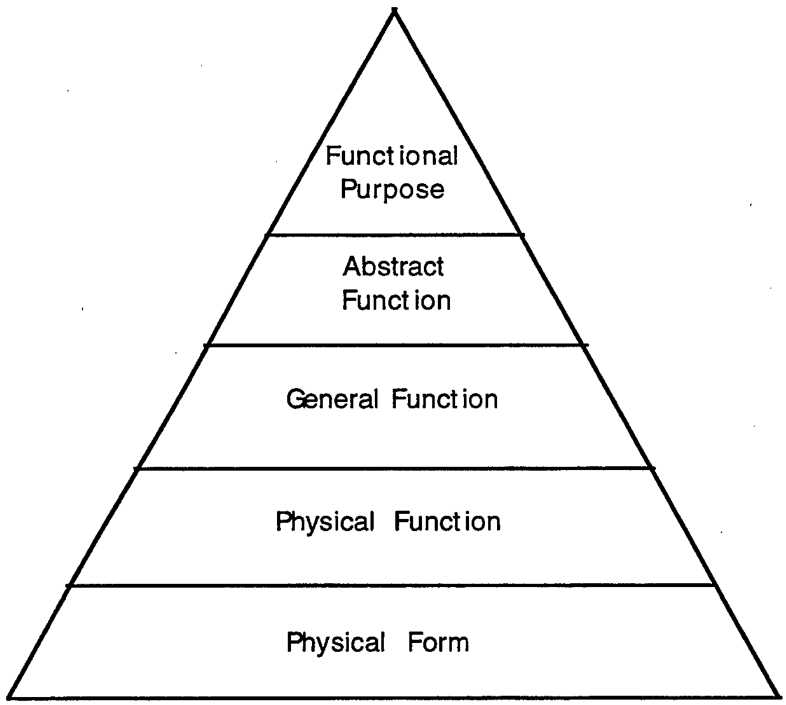


Figure II. Rasmussen's (1986) abstraction hierarchy represents a nested hierarchy in which relatively few categories provide a meaningful characterization of the functional purpose of a complex system, but many more categories are needed to meaningfully characterize distinctions in physical form.

Figure II shows how different analyses fit within the abstraction/ decomposition space for understanding the problem. Note that these different analyses fall along the diagonal of the analysis space and thus are consistent with the pattern seen in expert reasoning. Each analysis shown in Figure I. will be considered in turn in the major sections of this report. The report will proceed in a top-down fashion from consideration of goals and values to analysis of the space-time properties of specific activities. The analyses shown represent classical components to any systematic analysis of a complex control system.

A unique attribute of the CSE approach is an attempt to integrate across the component analyses to achieve a global understanding of the distributed control system. Top down relations along the diagonal help to uncover the underlying rationality of the work domain. This rationality provides the reasons why things are done or the reasons why things are significant. This is important to understanding the focusing-in problem of cognition. That is, what causes certain features to pop out in a way that allows experts to focus in on critical aspects of a problem early in the analysis. In other words, what is the basis for the high situation awareness achieved by experts. How is it that they can recognize good solutions as the first to be considered (e.g., see Klein, 1993)? Further, how can the interfaces be designed to facilitate these recognitional processes and to support high levels of situation awareness.

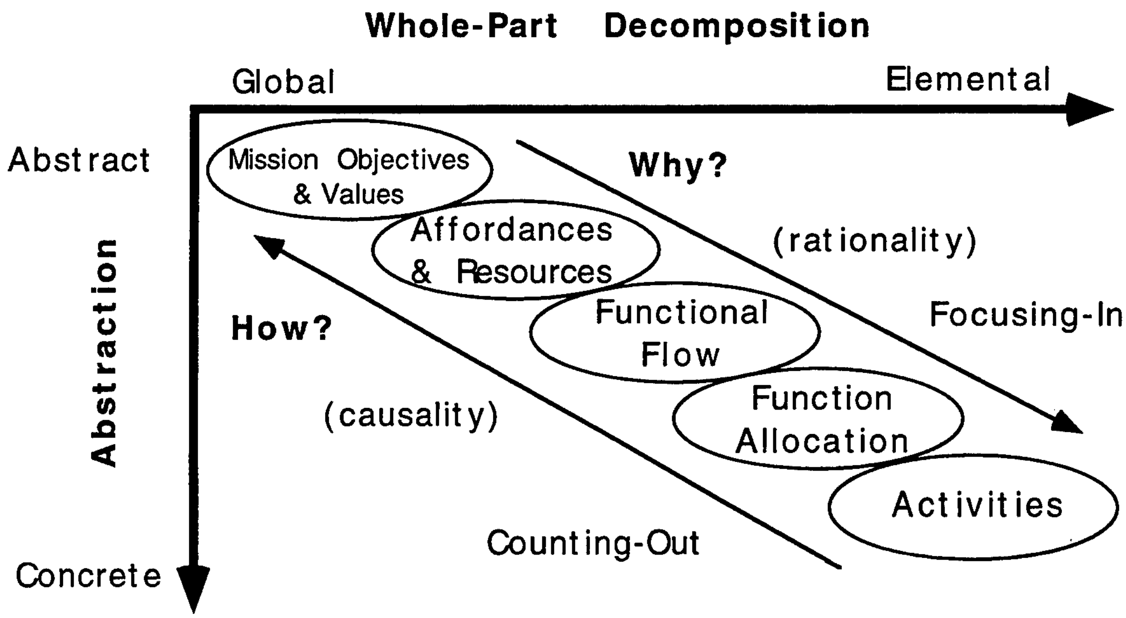


Figure III. An illustration of how different aspects of a cognitive task analysis fit within the overall analysis space defined by the abstraction and decomposition dimensions. Reasoning down the diagonal helps to reveal the rationality that determines why things are done. Reasoning up the diagonal helps to reveal the causal relations that determine how things are done.

Bottom up relations along the diagonal help to uncover the causal structure within the work domain. This causal structure provides a production like description of how things can be accomplished within the work domain. This kind of description is critical for the design of rule based, counting-out processes that are typical of classical artificial intelligence and expert systems. These relations can be critical in the design of automated systems. Automating the well-behaved (rule-based or routine) aspects of the work can free up human resources to be focused on supervising the "messier" aspects of the work.

Within the CSE approach the top down and bottom up relations are complementary perspectives that contribute to a complete understanding of the workspace. A primary goal of the cognitive system engineering approach is to make the links along this diagonal explicit (as opposed to an implicit understanding encapsulated within a particular analyst's experience). Unlike classical and modern (e.g., optimal) approaches to control systems that begin with restrictive assumptions (e.g., linearity, a quadratic cost function, etc.) in order to build quantitatively powerful models of the system, CSE focuses on the assumptions themselves. Classical and optimal control make assumptions that turn messy problems into well-defined problems that allow quantitative solutions. But CSE is all about the "messiness," because that is why operators are included in most control systems --- to deal with the messiness (the unanticipated variability). If the problems were well defined and met the limiting assumptions of classical or modern control models, then there would be no need for the human. The goal of cognitive engineering is to understand the messiness as the most interesting part of the problem. As a result, the models of CSE tend to rely more on the qualitative insights of control theory, rather than on the quantitative methods. This does not mean that quantitative models are not used or that they are not valuable tools for developing qualitative insights. But the quantitative models are not sufficient. In many respects, CSE is most important for exploring regions just outside the limits of a quantitative control analyses of the problem. These are the regions where automated solutions are likely to breakdown. These are the regions where human expertise is an essential ingredient for success. In this respect, CSE is a means of providing a qualitative glimpse over the horizon set by limits of our quantitative control models.

From a design perspective, CSE generally focuses on the nature of problem representations as a means for dealing with messy problems. Through the design of interfaces, CSE attempts to build representations that allows operators to directly perceive significant features of a problem (e.g., see Bennett, Nagy, & Flach, 1997; Flach & Bennett, 1996; Rasmussen & Vicente, 1989; Vicente, 1992; Woods, 1991). Rasmussen (1998) emphasizes that in building these representations, designers must look beyond the human-computer interface "to the interface between a decision maker and the deep relational structure of the work space." He presents a thorough review of ecological interface design in the context of SEAD/UAV systems. Through the design of training systems and protocols, CSE, helps to attune internal representations (in Rasmussen's (1986) terms, the dynamic internal model). to significant features of the problem (e.g., Flach, Lintern, & Larish, 1995; Flach, 1997). It is too early in the analysis process to speculate about interfaces or training programs for UCAVs. However, a long range goal for the analysis reported here is to ultimately inform decisions about interface and training program design.

In sum, the UCAV design problem can be characterized as a "messy" problem. The operational concepts are **U**nderspecified. The work domain of the SEAD mission requires a **C**ollaborative and **A**daptive human-machine system. Finally, this is a **V**ulnerable mission and technology. The mission is dangerous and the technology is relatively untested. The remainder of this report will work down the diagonal of Figure I.3 as a preliminary step to a more complete CSE analysis.

II. MISSION OBJECTIVES AND VALUES

This section considers the highest level of abstraction---the level of functional purpose. At this level, the fundamental question is---why does this system exist? The functional goals define the problem space in terms of a value system. This level represents critical dimensions for evaluating the "optimality" or "degree of satisfaction" associated with *outcomes* and thus provides the ultimate context for evaluating "success" or "failure." This is the level at which the "cost functional" relative to optimal control models might be considered.

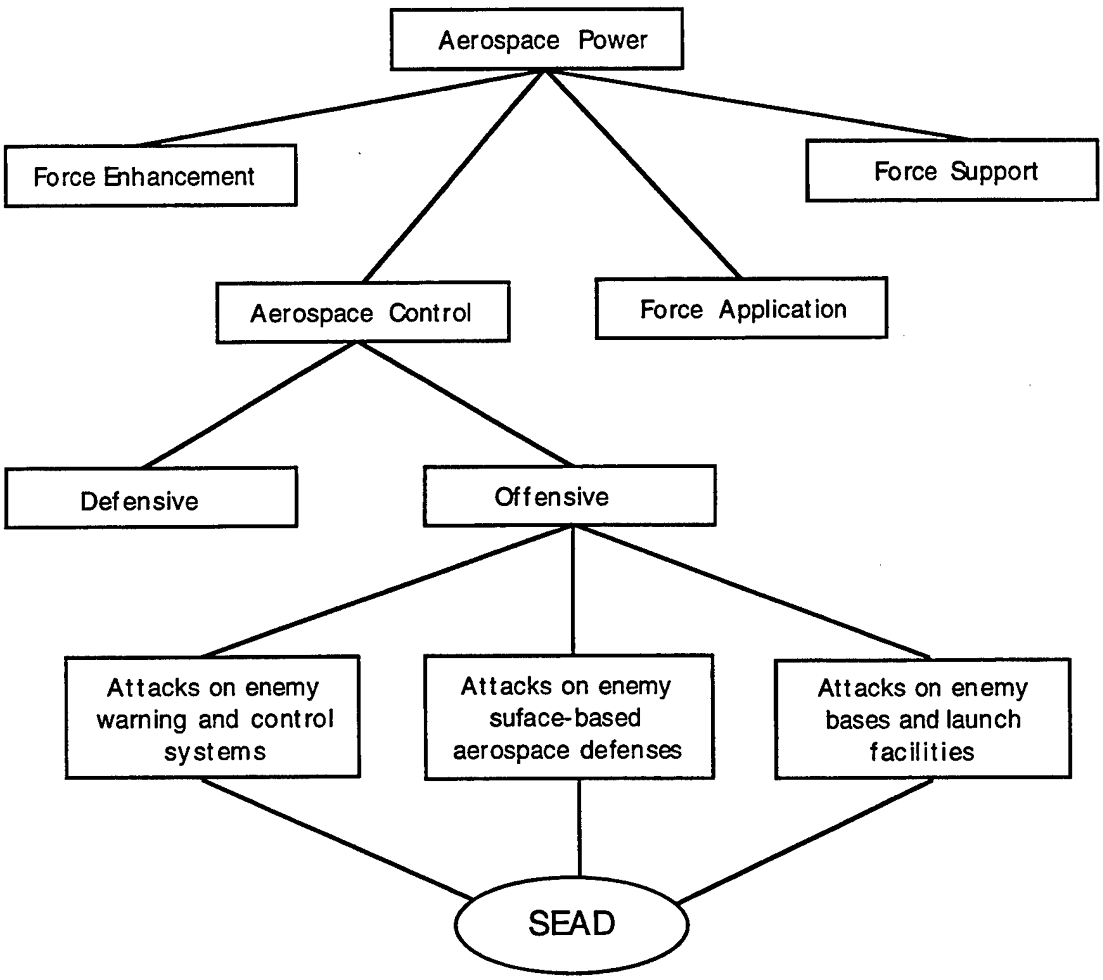


Figure IV. Decomposition of the general function of Aerospace Power. In this context the SEAD mission is an important subfunction of the general function of aerospace control.

At this level it is important to consider the UCAV/SEAD in the context of the global objective of the Air Force and in the context of general principles of war. Figure IV. shows the SEAD mission in the context of the more global function of Aerospace Power. Basic Aerospace Doctrine (Air Force Manual 1-1, 1992) breaks the general function of aerospace power into four sub-functions. Of these subfunctions, the function of aerospace control plays a prominent role---"aerospace control should be the first priority of aerospace forces" (Air Force Manual 1-1, 1992, p. 10). This function can be further decomposed into two subfunctions: offensive counteraerospace and defensive counteraerospace. In turn, offensive counteraerospace can be decomposed in terms of the target objectives: warning and control centers, surface based defenses, or enemy bases and launch facilities. In current discussions, all three target objectives are included within the SEAD mission. For example Air Force Manual 1-1 (1997) writes, "OCA operations include the suppression of enemy air defense defense targets, such as aircraft and surface-to-air missiles or local defense systems, and their supporting C^2." Localized SEAD generally refers to missions that target surface based defenses.

SEAD is defined as "any activity that neutralizes, destroys, or temporarily degrades enemy surface based air defenses by destructive and/or disruptive means" (Joint Pub 3-01.4, 1995). The definition makes the "objective" of the SEAD mission clear, but does not explicate the value system that might be used to compare alternative means for achieving that objective. If you wanted to compare two alternative designs for a UCAV, what attributes would be important to consider? To begin to address this question, we consider basic aerospace doctrine (Air Force Manual 1-1, 1992) which outlines nine principles of war:

Objective. Direct military operations toward a defined and attainable objective that contributes to strategic, operational, or tactical aims.

Offensive. Act rather than react and dictate the time, place, purpose, scope, intensity, and pace of operations. The initiative must be seized, retained, and fully exploited.

Mass. Concentrate combat power at the decisive time and place.

Economy of Force. Create usable mass by using minimum combat power on secondary objectives. Make the fullest use of all forces available.

Maneuver. Place the enemy in a position of disadvantage through the flexible application of combat power.

Unity of Command. Ensure unity of effort for every objective under one responsible commander.

Security. Protect friendly forces and their operations from enemy actions that could provide the enemy with unexpected advantage.

Surprise. Strike the enemy at a time or place or in a manner for which he is unprepared.

Simplicity. Avoid unnecessary complexity in preparing, planning, and conducting military operations. (Air Force Manual 1-1, 1992, Fig 1-1, p. 1)

Figure V shows one possible hierarchy for these nine principles. This hierarchical structure does not represent differences in priority. Rather, the hierarchy highlights functional interdependencies among the nine principles. These interdependencies may be critical for evaluating trade-off across competing goals.

The definition of SEAD above specifies the "objective" for the SEAD mission, which is the top node of the hierarchy. At this level, performance might be scored relative to the number of ground threats destroyed or disabled; in terms of the space and time over which the threats are suppressed; and/or in terms of the probability of survival. This level of description could provide a good measure of operational effectiveness for an actual SEAD mission, but it is difficult to score a "design" in these terms. One can only guess about whether a particular design innovation will significantly impact the destructive effectiveness or survivability of the system. Guesses may be informed by man-in-the-loop simulations and/or quantitative system models, but they are guesses, never-the-less that reflect the simulation or model designer's assumptions about what is valuable and about the nature of potential threats. However, because IADS are also evolving it is difficult to reliably extrapolate into the future. (SEAD enables airspace control—a higher level objective.)

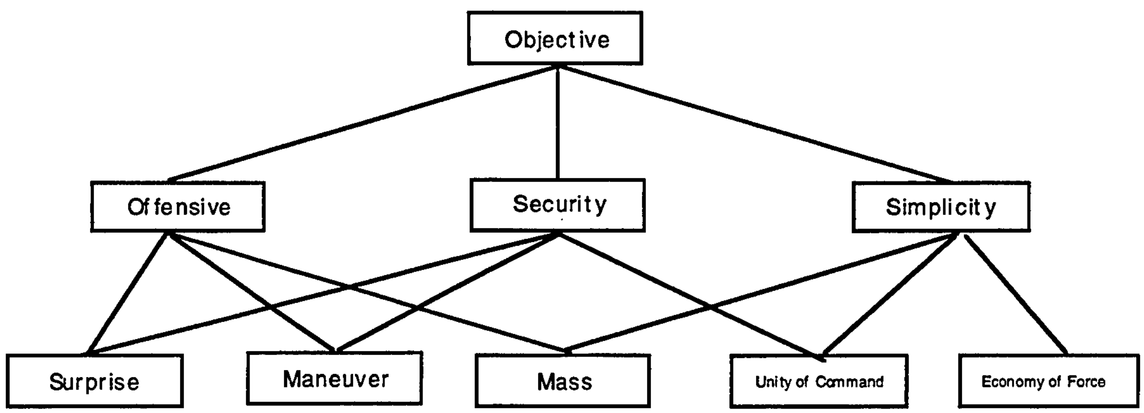


Figure V. A hierarchical representation of the nine principles of war. The dimensions at the base of the hierarchy will be used as dimensions of a value space for evaluating potential "means" for accomplishing the SEAD objective.

The next level, specifies some general values for evaluating alternative means for achieving a military objective (proactive, safe, and simple). The value of these dimensions is clear, but it is not clear how these abstract objectives could be measured. How do you quantify proactive, safe, or simple ---particularly when you are evaluating a design? The next lowest level provides more specific attributes for evaluating potential means. At this level, the values are stated in terms that might be measured and evaluated even in the design phase. Thus, UAVs described in Tables I. and I. 2 can be compared in terms of their stealth capabilities (surprise), their maneuverability, their fire power capability (mass), their command and control structure (unity of command), and their design and operation costs (economy of force). This lower level of the hierarchy may be particularly important for measurement and for meaningfully evaluating alternate means for achieving the ends of "neutralizing, destroying, or temporarily degrading enemy surface based air defenses."

The hierarchy in Figure V suggests how objective measures of the lower level goals might be integrated to make inferences about the higher level principles---and ultimately about success with respect to the specific objective to suppress enemy air defenses. This integration is critical for evaluating design trade-offs among the competing goals. For example, the decision to shift from the F4-G to the Block 50 F16s for manned SEAD missions is largely motivated by desires for simplicity and economy of forces. However, savings on these dimensions must be weighed against potential costs in offensive power---the ability to maneuver and mass the right forces to attack a SAM site. Concerns have been raised that the F-16's sensor capabilities (even with LANTIRN) are not as effective as the F4's and that the single F-16 pilot will not have the same capacity to manage the complex information as the 2-man crew of the F4. For example, North (1997) writes:

> *The single most limiting operating consideration for the HTS pod is that it has a field-of-view of 87 deg. either side of the F-16 nose. This is different than the 360-deg. coverage provided by the F-4G Wild Weasel. The Air Force has no plans at present to give the F-16 full 360-deg. coverage. The other limitation cited by some is the use of the F-16 for the HARM role is that the F-16 is a single-seat fighter, while the F-4 is a two seater. Another difference between the systems is that the F-16's HTS pod does not give an audio identification of the radar emission threat. [p. 153] Newer versions of F-16 (e.g., block 50) however, may mitigate these concerns..*

One way in which this kind of information is typically presented is in trade-off curves. How much is a specific increase in mass (e.g., weapons load) worth, in terms of costs to the ability to surprise (e.g., RCS)? In many cases, the level of quantification required to generate trade-off curves will not be available. However, the importance of a qualitative understanding should not be underestimated---this might be achieved by documenting consistencies and inconsistencies in information provided by subject matter experts (SMEs) about critical incidents or decisions that reflect these trade-offs. Thus, another form of data may be "cases" or "stories" that illustrate the underlying value system guiding choices and actions.

Brungess (1994) suggests four continuums that reflect the changes in the value system for evaluating the SEAD mission:

Piecemeal/integrated dimension. This dimension considers the degree to which the SEAD mission is integrated within a global mission to disable the IADS. Defensive SEAD (e.g., as practiced in Vietnam) tends to be a piecemeal, reactive response to localized threats. On the other hand, offensive SEAD (e.g., Desert Storm) tends to be a more integrated approach where SEAD is part of a joint services mission directed at global objectives to disable the total IADS structure. The trend is toward integrated approaches. In terms of Air Force Doctrine this continuum reflects movement toward a proactive attitude with increased unity of command. It also has implications for the economy of effort.

Need-based/resource-based dimension. This dimension considers the support available for SEAD missions. At the need-based end of this continuum the need takes precedence. This reflects a resource rich environment where political support of military objectives is a high priority. The resource-based end of the continuum reflects an environment where political support for military objectives is low. That is, the key consideration is how to most effectively utilize limited resources in order to achieve mission objectives. The current environment is closer to the resource-based end of this continuum, where the military is increasingly challenged to "do more with less." This obviously relates to economy of force.

Threat-based/Capability-based dimension. This dimension considers the degree to which strategies and tactics can be targeted to characteristics of a specific threat. For example, Cold War military tactics were largely tailored toward a specific enemy (the Soviet Union). However, now the "US SEAD community faces an unknown potential enemy that can field the best weapons Western arms industries are capable of selling them" (Brungess, 1994, p. 85). In a threat-based situation, it is much easier to define objective criteria for evaluation. However, the trend is toward more capability-based situations. As Brungess (1994) notes, this promises "to be vexatious." How do you evaluate "general capability" with respect to ill-defined threats? This dimension reflects constraints on how objective strategies and tactics can be.

Defensive/Offensive dimension. This dimension considers the degree to which SEAD serves in a defensive support role or as an offensive weapon. The trend appears to be toward increasing use of SEAD as an offensive weapon for attacking IADS.

These four dimensions of Brungess (1994) illustrate how political, economic, and technological forces have an impact on the tradeoffs among dimensions in the value space. Because of economic pressures and due to the lack of a single, well-defined enemy the SEAD of the future will need to be more fully integrated into an offensive, capability based strategy that efficiently utilizes limited resources. How do UCAVs meet these requirements?

To conclude our preliminary analysis of the mission goals and values, it is useful to again consider the general framework shown in Figure I.1. On the situation side of the equation, this level of analysis emphasizes the "ends" for the means-ends structure (1). These "ends" provide an important context for parsing the work domain in terms of tasks (2). These ends also represent key components to a "cost functional" for evaluating decisions (3) and strategies (4). On the awareness side of the equation, the values, such as the principles of war, are important aspects of the organization culture (6). The goal structure can also have important implications for team structure and role allocation (5).

III. AFFORDANCES & RESOURCES

This level introduces an abstract description that makes it possible to bound the space of possible or feasible design solutions. The term "affordance" was coined by Gibson (1979) to characterize the opportunities that the natural environment offers (or affords) an animal. Norman (1988) and others have extended application of this term as a key concept for characterizing the opportunities which are afforded by technologies as well as natural environments. At this level, consideration is given to the limiting technologies and resources for implementing the SEAD mission. What can UCAVs do? The objective, at this level, is to choose a language for characterizing the problem space that bridges between the functional goals and the physical constraints that bound approaches to those goals. For example, the flow of electromagnetic energy is critical to "surprise," and to identifying the location of targets so that weapons can be "maneuvered" and "massed" to the appropriate place at the right time. The flow of weapons and aircraft require that the "affordance space" include dimensions that reflect aerodynamic constraints on motion. At this level, aerodynamic constraints of particular aircraft are not considered, rather the general parameters of any aerodynamic system are considered as dimensions of the overall problem space.

A significant technology for the SEAD mission is the technology of electromagnetic or electronic warfare. Electronic warfare evolved during World War II in what Churchill called the "battle of the beams" or the "wizard war." This battle involved the development of electronic guidance aides by the Germans and counter-measures taken by the allies (Fitts, 1980). The use of electronic warfare related to the SEAD mission was further developed in response to the SAM missile threat during the Vietnam War.

Fitts (1980) defines **electronic warfare** as:

> *military action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum and action which retains friendly use of the electromagnetic spectrum (p. 1).*

Electromagnetic energy includes radio, radar, infrared, optical systems, and lasers. Fitts (1980, p. 2) specifies three divisions of electronic warfare which are shown in Table IV.

Table IV.

Electronic Warfare Support Measures (ESM) - involves "actions taken to search for, intercept, locate, record, and analyze radiated electromagnetic energy, for the purpose of exploiting such radiation in support of military operations" (p. 1). *
Electronic Countermeasures (ECM) - involves "actions taken to prevent or reduce the enemy's effective use of the electromagnetic spectrum" (Fitts, p. 2). It includes: Jamming - "the deliberate radiation, reradiation, or reflection of electromagnetic energy with the object of impairing the use of electronic devices, equipment, or systems being used by the enemy" (Fitts, p. 2). Deception - "the deliberate radiation, alteration, absorption, or reflection of electromagnetic energy in a manner intended to mislead the enemy in the interpretation or use of information received by his electronic systems. There are two categories of deception. (1) Manipulative - the alteration or simulation of friendly electronic radiations to accomplish deception. (2) Imitative - introducing radiation into enemy channels which imitates his own emissions" (Fitts, p. 2).
Electronic Counter-countermeasures (ECCM) - involves "actions taken to insure friendly effective use of the electromagnetic spectrum despite the enemy's use of EW" (Fitts, p. 2).

At this level of analysis it is important to understand the fundamental principles of electromagnetic energy and how these principles constrain sensor, display, and weapon technologies. Table V. below (from Fitts, 1980) shows a somewhat dated list of how parts of the electromagnetic spectrum are utilized for some typical location systems. Although dated, this list helps to convey a sense of how the spectrum is typically used.

One of the goals for this level of analysis is to give an abstract characterization that suggests measures that will help to connect decision about function allocation and the design of the physical system (lower levels of abstraction) with the functional goals at the highest level of abstraction. As noted by Brungess (1994) this can be a problem:

> *Since the electromagnetic spectrum is the medium with which modern defense suppression works, the criterion of counting bomb craters, measuring distances from intended impact point, or assessing hits per try is more difficult to apply. Wave fronts of electromagnetic radiation are invisible: the theory of their propagation is not easy to explain --- nor is it easy to counter an adversary's use of the spectrum. . . . Many tactics and strategy analysts try to place SEAD effects in the realm of the observable without clear references to the overall objective SEAD supports (p. 52)*

* Note: Electronic Warfare Nomenclature continues to change. Currently the terms electronic protection and electronic attack are favored over the older ESM, ECM terms used in Fitts, 1980.

Table V. Spectrum Utilization of Typical Military Location Systems
(from Fitts, 1980)

Frequency Band	System	Range (NM)	Accuracy (max)
VLF (3 - 30 kHz)	OMEGA	5000	1 mi
LF (30 - 300 kHz)	GEE		
	LORAN C/D	1200/500	.02 - .1 mi
	DECCA	300	.1 - 1 mi
MF (300 - 3000 kHz)	ADF	300	2 deg
	STD LORAN	700	5 mi
HF (3000 - 30,000 kHz)	OTH Radar	1000	1 mi
VHF (30 - 300 MHz)	VOR	200	3 deg
	EW Radar	300	1000 ft
	BMEWS	2000	1 mi
UHF (300 - 3000 MHz)	TACAN	200	1 deg 1000
	GCI Radar	150	mi
	SAM Radar	10 - 100	500 ft
	AAA Radar	20	100 ft
	IFF	300	100 ft
SHF (3 -30 GHz)	Airborne Mapping Radar	100	50 ft
	Airborne Intercept Radar	30	50 ft
	AAA Radar	20	50 ft
Infrared	Tail Warning	5	
	FLIR	5	
Optical	AAA Control	1 - 10	
	LLTV	5	

The capabilities of electromagnetic sensors are one set of design constraints. However, there are many other sources of constraint that bound the design space for UCAVs with respect to the SEAD mission. Table III.3 presents brief descriptions of some of the general categories of constraints that might be considered in an analysis of affordances and resources for the SEAD mission.

Table VI.

[illegible]
Aerodynamics - at this level the laws of aerodynamics set critical boundaries for how high, far, fast, etc. a platform can fly and for the consequences of those actions (e.g., g-forces, energy cost, etc.). Some of the aerodynamic constraints (e.g., maximum speed and climb rate) of UAV platforms are listed in Table I.1.
Sensor Technology - at this level focus is primarily on the electromagnetic spectrum and the technologies for sensing electromagnetic energy (e.g., radar, infrared and optical systems). Table I.2 lists some of the sensors that will be utilized on various UAV platforms. What are the functional relations or laws that constrain range, resolution, field of view, etc.? How does this electromagnetic energy map on to the objects of interest?
Interface Technology - this level focuses on the properties of controls and displays. What are the constraints on the representations that can be constructed at the human-machine interface? Fundamental constraints on resolution, gain, field-of-regard, level of detail, etc. are considered at this level.
Weapons Technology - this level considers fundamental constraints on weapons systems. Issues include size, accuracy, launch constraints, destructive capacity, guidance systems, etc.
Communication & Control - this level considers constraints on communications systems and their implications for stability and control. Table I.2 lists some of the communication technologies that will be utilized in various UAV platforms. Signal-to-noise and time delays are particularly important considerations here. Time delay for Dark Star and Global Hawk are in the range of seconds.
Information Processing - this level considers the computational capacity of the system (the capacity to differentiate and integrate information). Issues such as information processing rate and memory capacity (both working and long-term memory) are considered here. Important issues here are the constraints that determine "bottlenecks" or "chokepoints" in the flow of information. Both automatic and human information processing is considered here.
Rules of Engagement - the rules and conventions of war are considered at this level. Considerations at this level include international law and national policy as well as military doctrine.

Each category in Table VI. represents a different basic scientific discipline. It is clear that design of complex systems like a UCAV system is a multidisciplinary endeavor. Coordination across the various disciplines can be critical to successful design. Cognitive systems engineers can not be expected to know all the critical information across these disciplines, but cognitive engineering can help to facilitate interactions across the various disciplines. One way to do this is to make the relations between the mission objectives/values and technological constraints as explicit as possible. Thus, the mission goals provide a common currency to promote dialog across the various disciplines. Explicating the relations between technological constraints and mission goals can help to organize these basic scientific data in such a way that those outside the specific disciplines can appreciate the significance of the scientific laws and principles relative to the SEAD mission.

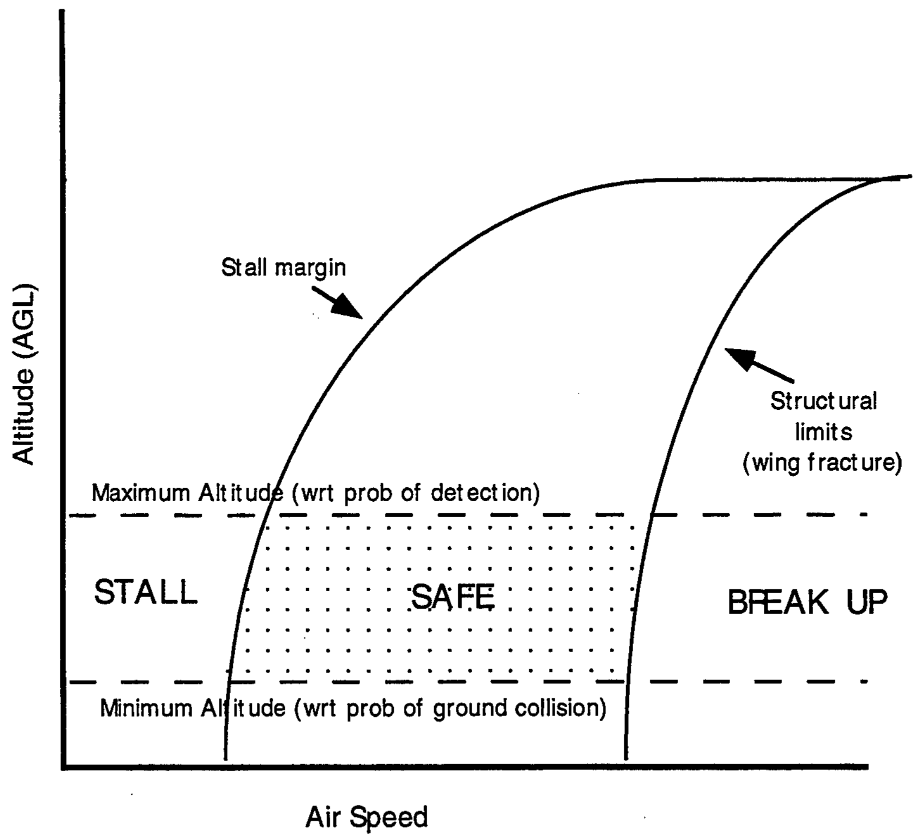


Figure VI. A state diagram provides a representation to conceptual bridge between the "physical law based" constraints (e.g., aerodynamic constraints) and "value based" constraints (e.g., the goals of maneuvering mass in a way that will surprise the enemy). The abstract function level of analysis attempts to identify the dimensions of this state space. The boundaries within the space reflect higher order goal (e.g., avoiding detection) and lower lever physical constraints (e.g., stall boundary).

One kind of representation that can be very effective for representing the interaction of "physical law based" (affordances) and "value based" (mission objectives) constraints is the state space diagram (Figure VI.). The dimensions of the state space diagram are variables that reflect the underlying physical dynamics. The boundaries within the state space can reflect either law based physical constraints (e.g., the stall margin) or value based constraints (e.g., boundary defined by probability of detection by enemy radar). Integrating these constraints into a common graphical space helps to visualize the "possibilities for action," "affordances," or the potential "safe" regions of operation as illustrated in Figure VI. Kirlik (1995) provides a good illustration of how visualizing the values and physical constraints can provide a basis for predicting expert behavior in a complex synthetic task for helicopter crews.

The key considerations at this level are not the particulars of a specific constraint such as the stall boundary illustrated in Figure VI., because this reflects details of the physical form of the aircraft (e.g., wing shape). Rather, the level of abstract function specifies the dimensions of a problem space representation which reflects both the constraints of the physical systems and technologies (which will be considered in detail at lower levels of analysis) and the values and goals (which were discussed in the previous section). The value of the abstract function level is to bridge between the top-down rationale constraints reflected in the goals and purposes of the system and the bottom-up causal constraints that arise from the particular physical instantiations of the system. Thus, the point is that if your goal is to fly weapons and sensors into a battle, then speed and altitude will be critical dimensions that need to be considered as part of the overall problem space.

There is an interesting discussion in the SAB report on UAVs (SAB-TR-96-01) of how the maximum altitude for the UAV (which reflects fundamental law based constraints on line-of-sight communications) interacts with vulnerability to potential threats:

> *Altitude* - Sensor and communication link line-of-sight reach is the primary driver, with survivability second. An altitude of 65,000 ft offers over 300 nm to the radio horizon (disregarding multipath difficulties) and over 100 nm for 5 degree grazing angle SAR (synthetic aperture radar) or MTI (moving target indicator). Flying at altitudes above 5,000 ft defeats most radar directed guns and above 15,000 ft defeats most shoulder launched homing weapons. Altitudes greater than 60,000 ft defeat the bulk of older SAMs and above 70,000 ft prevent fighters from reaching co-altitude. However, even at 70,000 ft air-to-air missiles can be launched to higher altitudes. (Worch, et al., 1996, p. 4-1)

The SAB also discusses how endurance (determined largely by aerodynamic constraints) reflects on the value system in terms of economy of force:

> *Endurance* - the value of endurance is primarily in the economics of fleet size necessary to maintain one vehicle continually on station and secondarily in the flexibility of basing far from the theater of action. On-station to transit-time ratios of less than 1:1 require more than two vehicles (plus backup) to maintain one on station. An operating radius of 6,000 nm to station allows CONUS (Continental US) basing to cover most of the world. A nominal 3,000 nm radius allows nearly world coverage from four politically secure bases (Roosevelt Roads, Mildenhall, Diego Garcia, Guam). A 1,000 nm radius is sufficient for most in theater sanctuary operations. (Worch, et al., 1996, p. 4.2)

These two samples from the SAB report are representative of how physical constraints and values interact in evaluating design solutions. The relations between functional objectives and technological limitations are critical considerations for design. These dimensions specify the design problem space. This space provides an important framework for discussions between the Air Force Command (who specify what is desirable, in terms of performance objectives and cost) and the technical engineering community (who are most knowledgeable about the technological means for accomplishing the performance objectives). Again, this level of analysis provides a framework for integrating over the intentional and physical constraints to identify satisfactory solutions. Cognitive engineers are typically the experts on the human information processing component. However, they can also play an important role in managing the cross disciplinary market place where many disciplines contribute to a complete understanding of the problem.

In terms of Figure I., consideration of the affordance and resource constraints sets the ultimate boundary conditions for "means" to achieving the systems "ends" (1). The affordances and resource constraints set feasibility boundaries and help to dimension the trade-off curves for evaluating the criticality of tasks (2) and the optimality of decisions (3) and strategies (4). One would expect that skilled operators would have an implicit understanding of the affordance and resource constraints that govern performance in a work domain and that this understanding would be reflected in their decision making and their choice of strategies.

VII. FUNCTIONAL FLOW

This level of analysis decomposes the SEAD mission into functional processing blocks or stages. At this level of abstraction it is desirable to have a level of decomposition that allows clear specification of the inputs, outputs, and goals for each process. However, the descriptions should be general enough to cover a wide range of specific design options. That is, the decomposition should not be specific to a particular design (e.g., UAV versus manned). Thus, the functional flow at this level does not reflect any particular function allocation. The components represent processing requirements, with no commitment to whom (which crew member) or what (automated system) will carry out the processing. Figure VII. shows some possible decompositions.

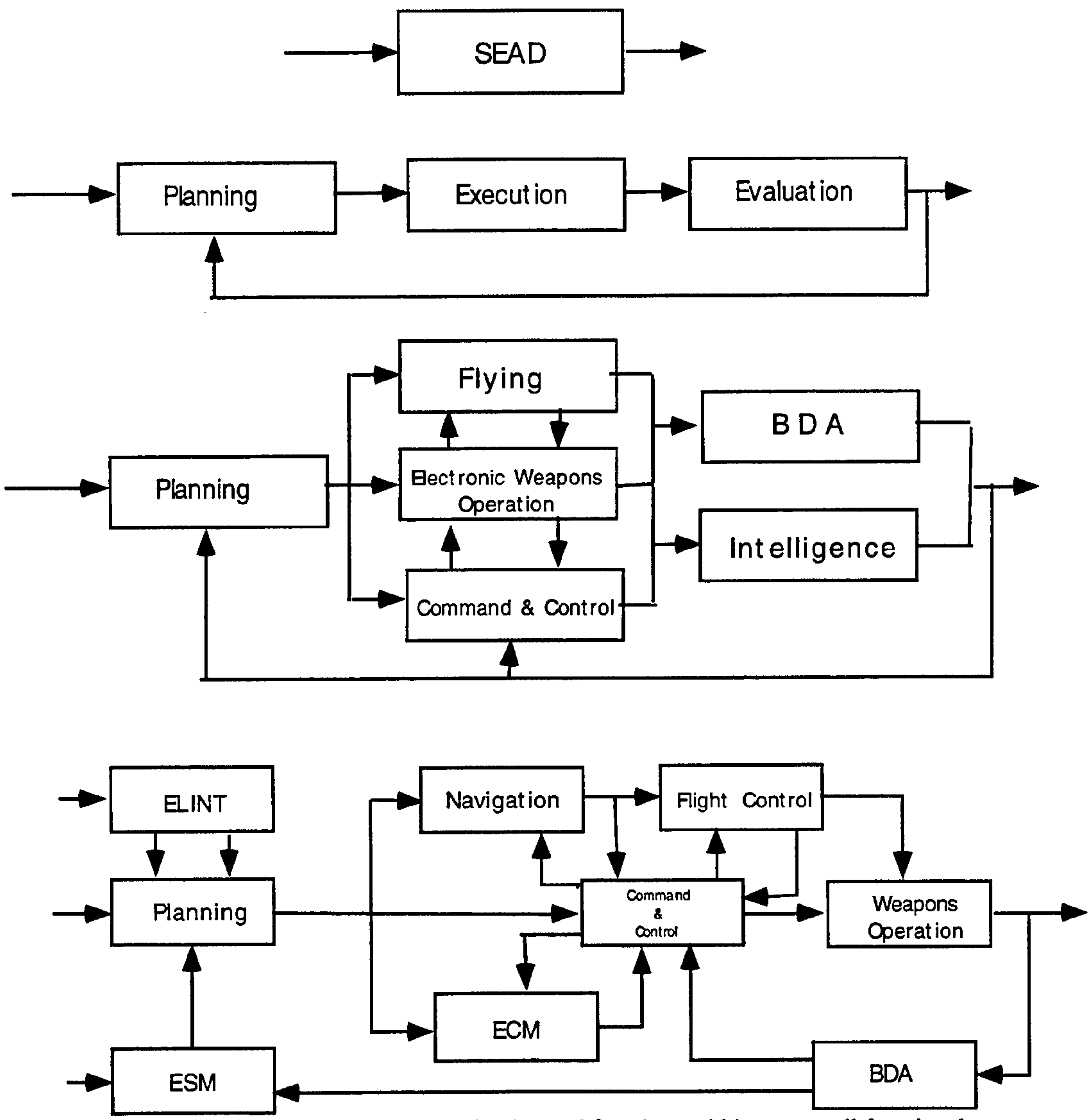


Figure VII. A decomposition of the SEAD mission into subfunctions within an overall functional flow.

The lower flow graph in Figure VII. represents a first hypothesis about an appropriate decomposition for this level of analysis. Each of the subfunctions in this graph will be considered in turn.

ELINT - specific agencies within the military are tasked with the mission of collecting intelligence. Intelligence gathering is an ongoing operation. Intelligence provided by these agencies undergoes extensive analysis and represents a time frame greater than 24 hours prior to takeoff. This intelligence not only contributes information used in planning a specific SEAD mission, but also contributes to long range development of technologies and tactics.

Fitts (1980) describes the nature of intelligence with regard to electronic warfare:

The foundation of the whole subject of electronic warfare rests upon well-developed knowledge of the enemy electronic systems. This is the proper function of intelligence. It requires a long term effort and it culminates in the specification of the capabilities of the enemy weapon systems (Scientific and Technical Intelligence), the disposition of the enemy weapons (specifically the Electronic Order of Battle), and the strategy the enemy will use in the employment of his weapons (his battle tactics). This information is necessary to develop effective weapons and tactics, and to target our weapons to obtain our objectives. Thus intelligence, or the lack of it, forms the backdrop for the combat that is electronic warfare (p. 36).

Input from the ELINT component provides the background for mission planning. Input to the ELINT component comes from a variety of sources. The ELINT component links the SEAD mission to higher level control loops that reflect the larger historical context of the mission and the larger goals of the Joint Forces Command with respect to air superiority.

Table VII. outlines three stages of ELINT to determine the "fingerprint" of an electromagnetic transmitting site (Fitts, 1980).

Electronic Support Measures (ESM) - this component represents an additional source of reconnaissance that provides inputs to the planning function. Fitts (1980) contrasts ESM with ELINT:

When the tactical commander comes to the point of planning tomorrow's mission ... he needs more than this extensive background information [ELINT]; he also needs to know the precise state of the enemy's electronic defenses. It is not enough to know that there are so many AAA sites and SAM sites in the defense, he wants to know precisely where they are located, whether any have moved since the previous day, and if any new ones have appeared. He is also vitally interested in their tactics, e.g., if they have tried new approaches to defense. The value of the information to him is directly proportional to its currency. Hence, he has a legitimate need to request that certain reconnaissance be performed to satisfy his immediate needs. This reconnaissance is ESM because it will be quickly processed in response to the tactical commander's needs. The sources of ESM may be diverse; it may come from a regularly scheduled collection mission, or it may come from the debriefing of aircrews returning from the previous mission. In any case it will be subject to a minimum of formal analysis because of time constraints (p. 37).

Table VII.

Three Stages of ELINT (Fitts, 1980)
<u>Raw Data Collection</u> - the information which a receiver can determine from a signal are: a. Receiver power - which depends on the distance and orientation from the transmitter. b. Signal spectrum. c. Signal envelop d. Time variation - these are the gross variations due to antenna scan or transmitters being turned off e. Signal polarization - the orientation of the electric field in the signal f. Direction of the transmitter from the receiver.
<u>Analysis</u> - the components of the fingerprint which the collector would like to determine are: a. Transmitter power (must know distance from the transmitter to receiver) b. Carrier frequency (usually can be derived from the spectrum) c. Modulation (can be determined from spectrum and the envelop of the signal) d. Antenna Pattern (requires analysis of the time variation of the received signal at a moving collection point) e. Antenna scan (if the antenna moves in a consistent fashion, such as radar antenna, then the antenna scan may be determined from the time variation of the signal. f. Transmitter location (range and bearing)
<u>Collation</u> - the ultimate goal of electronic reconnaissance is to determine the following: a. Equipment characteristics (scientific and technical intel) 1. Transmitter power 2. Antenna Type 3. Frequency 4. Modulation 5. Special characteristics b. Geographical location (order of battle) c. Operational procedures (operational intelligence) d. Equipment use and capability (the threat) e. Messages transmitted (COMINT)

Planning. Planning is critical to the success of any complex mission. Key considerations for SEAD mission include information about the location and emitter characteristics of potential targets. As North (1997) notes the HARM Targeting System (HTS) "only looks for what it has been programmed to see. The sequence of emitters to be picked up --- based on their capabilities, performance and operations --- can be preprogrammed into the cassette, which is inserted in the front cockpit" (p. 151). SEAD missions are typically flown with four F-16s who fly a Combat Air Patrol (CAP) orbit. This CAP orbit would typically be a figure eight or bow tie type orbit with the horizontal axis aligned in a way to allow the HTS to scan the locations of the highest priority emitters. This type of orbit insures that the target area is in view of at least one of the HTS pods at all times. The SEAD mission must be planned in coordination with other functions in the joint area of operations. Joint Pub 3-01.4 outlines important planning considerations for the Joint Suppression of Enemy Defenses (J-SEAD).

Navigation. The navigation function is directed at getting the sensors and weapons to the right place at the right time. The function has typically depended on charts and visual, magnetic, and inertial references. However, the availability of the global positioning system (GPS) allows precise information about position and velocity. The availability of GPS can greatly increase the precision of navigation and it eliminates the need for many of the computations that were required before the availability of the Navistar satellites. However, methods for jamming GPS are already being developed. Thus, a system that depends on GPS for navigation may be vulnerable in the future.

Flight Control. In addition to normal precision requirements involved in flying the CAP orbit in coordination with other aircraft, the pilot must be able to orient the plane for optimal weapons release and must be prepared to maneuver to evade SAMs. Trussel (1997) writes "generally the best way to defeat a SAM is to fly away from it as soon as possible. This extends the distance the SAM has to fly causing it to run out of fuel before it gets to you. If the launch is very close or you can't turn away soon enough you could try the last ditch maneuvers. The maneuvers varied based on the type of SAM coming to kill you but they were all hit-and-miss (pun) at best" (p. 6).

Electronic Counter Measures (ECM) - this function involves the use of penetration aids (penaids) that allow a force to reduce the risks associated with penetrating a hostile defense. The majority of penaids are directed against radar, since these are often the eyes of the enemy. There are two general classes of ECM --- Jamming and Deception. Another facet of ECM is RHAW (radar homing and warning). Fitts (1980) notes that "the easiest RHAW task is to alert the crew members that signals are present; but that is only useful in sparse signal environments, in a dense environment such a warning is trivia....The most difficult RHAW task is to determine the direction of the threat, since this implies multiple antennas to achieve directivity or an analysis capability over a period of time" (p. 74).

Command & Control The command and control function is the heart of the control system. This function closes loops at multiple levels. The command and control function links the inner loops that control activities to the outer loops that relate the activities to the planned mission goals. It also coordinates the activities of multiple components involved in a SEAD mission. The SEAD mission typically involves multiple aircraft. Classically, a SEAD mission may have involved a hunter (F4) - killer (F15) team, several stand-off jammers (e.g., Compass Call or Rivet Joint), and the attack force that the SEAD mission is supporting. Current tactics using F15s or F16s typically employ four aircraft that fly a coordinated pattern to ensure that the target space is always illuminated by at least one of the forward looking HARM targeting systems.

Weapons Operation The current weapon of choice for the SEAD mission is the High-Speed Anti-Radar Missile (HARM). HARMs can home in on radar emissions and track back to destroy the source (antenna) of those emissions. This effectively blinds the SAM site, but depending on the position of the antenna to the launch facility may do little or no damage to the missile launch facility. Thus, a SAM site may only be temporarily disabled as a consequence of a HARM hit. A destroyed antenna can be replaced in a matter of hours. The HARM range is greater than 70 nautical miles. It is estimated that the missile will travel the first 10 nm in 30 s and the next 10 nm in 1 min. According to Shaw (1997) "there is a block upgrade program under consideration that would add an inertial measurement unit and a Global Positioning Unit receiver to the HARM for point-to-point targeting" (p. 153). If the HARM can not find an appropriate target, it will destroy itself.

Battle Damage Assessment (BDA) Battle damage assessment closes the loop between command and control and weapons operation. Real time assessment of the damage inflicted by weapons is critical for assessing the next move within the SEAD engagement. What targets have been eliminated? What targets remain? Where should the next HARM be directed? The BDA function also provides information for ESM relative to near term missions and for longer term mission planning. It is important that the BDA be framed within the context of the IADS. That is, a simple count of percent targets hit is not the issue. The question is what is the current state of the IADS? What level of damage has been inflicted and what capabilities remain?

Summary At the function flow level of description the system is described as a nested set of control loops. This helps to specify the task situation (2) and the decision tasks (3) with respect to Rasmussen's analysis framework (Figure I.1). The functional flow decomposition can help in visualizing the flow of information and the logical coupling between information and action and the couplings among decisions and actions across different levels of the nested control system. These couplings may have important implications for what strategies (4) might be successful in terms of a stable control system.

V. FUNCTION ALLOCATION

At this level, consideration is given to allocation of functions within the human-machine system. In principle, functions should be allocated with consideration to:

1) constraints on the functions themselves,
2) the capabilities of the potential agents (both human and automated), and
3) the overall structure of the team.

These considerations are outlined in Table V.1. The goal would be to allocate functions in a way that would lead to a high probability of satisfying mission goals and that would efficiently utilize the available resources. This is a particularly difficult and challenging design issue for a collaborative, adaptive system, because the criteria listed in Table V.1 can change dynamically with shifting contexts. For this reason, satisfactory function allocation can not be done *a priori*, since no fixed allocation will be optimal (or even satisfactory) across all the changing demands created by the dynamic context of the SEAD mission. The system must be designed so that responsibilities and roles can smoothly shift to reflect changes in, for example, the situation awareness and workload of the various cognitive agents. The problem of coordinating among multiple cognitive agents [including multiple human operators (e.g., pilot and electronic weapons officer) and multiple automated systems (e.g., UAVs, automated planning and decision systems)] is a critical challenge for designing a UCAV system for the SEAD mission.

The introduction of the UCAV as a new technology for the SEAD mission raises important concerns about the allocation of function. How much can we expect this new technology to do? How does the integration of this new technology change the roles of the other components (team members) in the collaborative system. There have been projections that a single human operator may have responsibility for multiple (4 to 6) UCAVs. Is this realistic?

A first step, in considering function allocation is to examine existing systems. There are two directions that might be taken here. One is to consider current systems for accomplishing the SEAD mission. These are currently manned systems. The other direction is to consider current UAV systems, which are primarily used for reconnaissance and surveillance. In this report, emphasis will be on the SEAD mission. However, a more complete analysis should also consider how the constraints that are inherent in the UAV technologies impact the role of operators. Most significant among these constraints is the long time delays between command centers and the UAV platforms. Note that for systems such as Global Hawk and Dark Star the time delay is on the order of seconds. This makes direct control of flight very difficult. As a result, the human operator is more likely to function as a supervisory controller (assigning waypoints and/or choosing among preprogrammed flight protocols), rather than as a manual controller (directly controlling flight surfaces).

Table VIII.

Level	*Key Considerations for Function Allocation*
Functions	**Priority**. Relative importance or criticality of a particular function. Is it essential or discretionary with respect to the overall mission objectives? **Precedence Constraints**. Sequential dependencies across the functions. To what extent do functions depend on the successful prior completion of other functions? **Temporal Constraints**. Are there fixed windows of opportunities or fixed time schedules associated with particular functions? **Spatial Constraints.** Does performance of the function depend on being at a particular place or location?
Agents	**Structural Understanding**. Does the agent have the appropriate knowledge or know how (e.g., right training for operators or right programming for automation) to accomplish the functions? **Information Availability**. Does the agent have adequate information (good situation awareness) for completing the function? **Resource Availability**. Does the agent have adequate information processing capacity (e.g., attention, memory, computational power) or physical capacity (e.g., free hand) to accomplish the function? **Effector Capability**. Is the agent capable of performing the actions necessary to complete the function? Can the agent respond in time with the appropriate precision?
Team	**Shared Mental Models**. Do the cooperating agents have a common or compatible vision (e.g., common assumptions, shared rationality) of the problem domain? **Information Coupling**. Is there sufficient information for each agent to know what and how other agents are doing? **Effector and Resource Complimentarity**. Do the effector and resource capabilities of the team span the demands of the work domain? **Authority Structure**. How are dynamic decisions about allocation handled (e.g., central authority, first-come, consensus, volunteer, etc.)? How are conflicts resolved?

V.A. Wild Weasel.

The Wild Weasel aircraft were designed to counter the SAM threat during the Vietnam War. A two-seat aircraft (originally F-100F Super Sabers, later F-4s) was configured so that the backseat operator had a radar homing and warning system (RHAWS) that could be used to determine the location of active SAM sites. The back seat operator was an electronic warfare officer (EWO) more commonly referred to as a Bear (or Gray Bear). The Wild Weasel mission was extremely dangerous. Clancy (1995) notes that "being on a Weasel crew was statistically suicidal in the early years of the Vietnam conflict." A typical tactic, code named Iron Hand, involved a formation of four aircraft attacking a SAM site that threatened the strike force. Typically, two Wild Weasels would carry air-to-ground missals and two more would carry more conventional bombs or cluster bombs.

With reference to the functional decomposition shown in the lower part of Figure IV.1 the EWO (or Bear) had primary responsibility for navigation, ECM (electronic countermeasures), ESM (electronic support measures), and weapons operation. The pilot was functionally a "bus driver" (quote from an anonymous EWO) who was primarily concerned with flight control. Although the pilot was always formally in command, much of the information for setting target priorities and evading threats was presented on the RHAWS, so the Bear was functionally very much involved in the moment-to-moment command and control decisions. The Bear had electronic information for BDA, but the pilot was in a better position to visually assess battle damage.

It is likely, that the "bus driver" function of flying will largely be automated in a UCAV system. Thus, the UCAV operator may function more like a Bear, than like a pilot (although the current operational Air Force UAV, Predator, is controlled by a qualified pilot).

V. B. Summary

At this level of analysis consideration is given to the resources and preferences of individual agents (7) with respect to the problem of role allocation (5). One can begin to match the requirements (tasks (2), decisions (3), strategies (4)) that are reflected in the functional flow to the resources and preferences of various cognitive agents (7). In addition, it is important to understand the management style and culture (6) in order to understand how organizational constraints shape the allocation of function. For example, will the Air Force permit nonpilots to be the command authorities of unmanned combat aircraft or will the pilot centered culture demand that pilots retain authority, even for unmanned vehicles?

VI. ACTIVITY ANALYSIS

The activity analysis represents the most detailed level of analysis. This level of analysis examines the behavior of the system, generally with respect to the dimensions of space and time. What actions or procedures are done; when; and where? For example, Figure X (from Worch et al., 1997) gives an example profile for a SEAD mission. Compare this representation to the functional flow diagrams shown in Figure VII. The connections in Figure VIII represent the flow of information within control loops. The connections in Figure VIII represent order in time (sequence) --- plan, take-off depart, enroute & orbit, acquire target, attack, return to orbit, etc. The boxes in Figure VII represent the processing of information. The boxes in Figure VIII represent activities that have a start and an end. The feedback arrows in Figure VIII represent control loops (information feedback). The feedback arrows in Figure X represent iteration loops (i.e., activities that might be repeated).

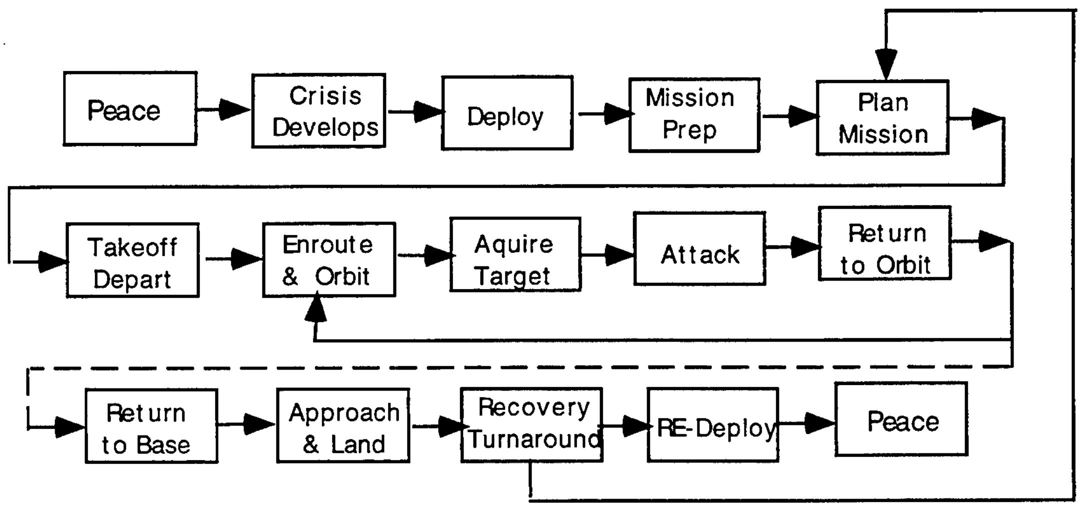


Figure VIII. A profile of the flow of activities for a potential SEAD mission (from Worch, 8 Oct 1997).

An alternative representation for activities is a spatial map. For example, Figure IX shows a segment from a SEAD mission flown by two F4-Gs. At Point 1 the two F4 s turn toward the SAM site to "stimulate the environment" and begin "working" the target. At Point 2 the radar signals from the SAM site are detected and the F4s split and begin flying tangent to the target. This tangent path allows the targeting systems to get multiple lines of position (LOPs) so that range to the target can be computed precisely. At Point 3 accurate range information has been acquired. However, the SAM has locked on and targeted US2. US2 begins evasive action and begins an egress from the target to create time and distance between it and any missals. At the same time, US1 turns toward the SAM and at Point 4 releases a missile ("Magnum, magnum!") in the direction of the threat. US1 then turns to egress from the SAM engagement.

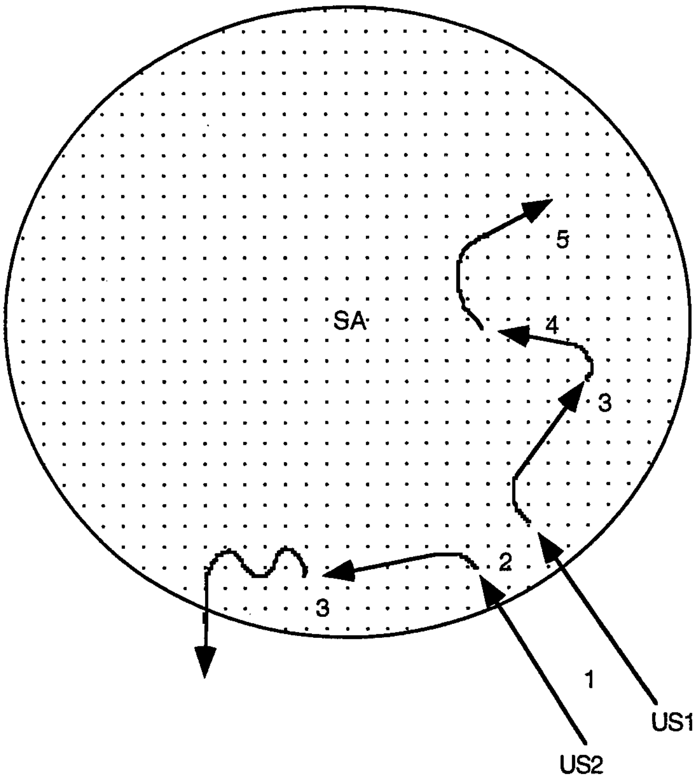


Figure IX. Two F4s work a single SAM site.

A time-line is another format for characterizing the events. Figure X was taken from an account of a training mission with two aircraft equipped with the harm targeting system (HTS) (North, 1997). This representation shows the sequence and relative timing of events. Annotations indicate some spatial aspects of the mission that are not graphically represented in this format. In this particular sequence, one aircraft's targeting system malfunctions. A data link is established and this plane is able to launch on the SAM sites using target information from the HTS of the second plane.

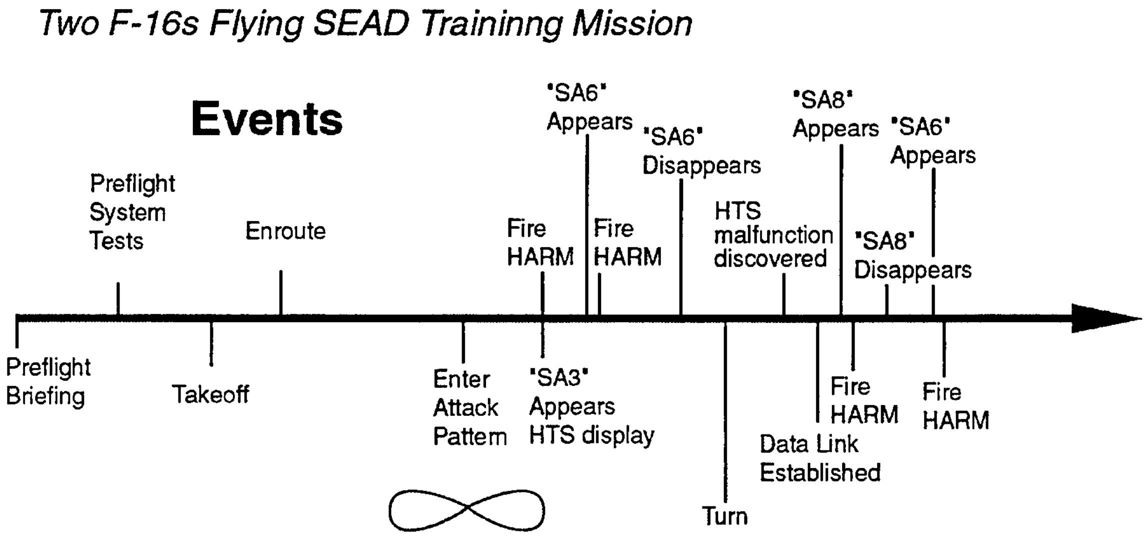


Figure X. A time line showing the sequence of events during a two aircraft training mission using the harm targeting system (North, 1997).

Another format, Figure XI (Shalin & Jaques, 1997), is for showing space-time properties of a generic mission. This particular representation shows altitude as a function of time.

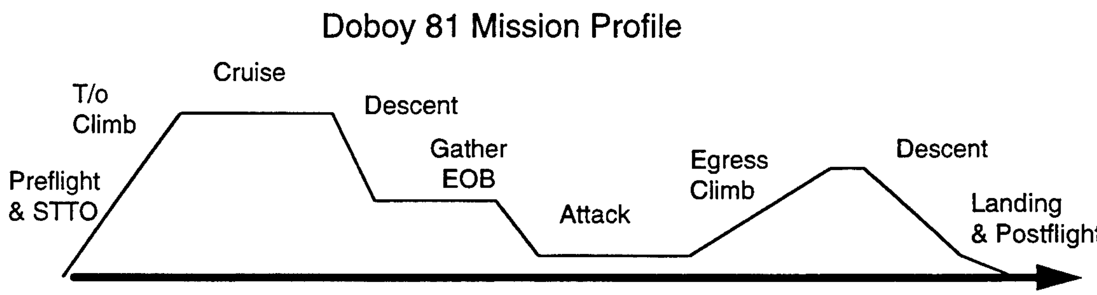


Figure XI. A mission profile for a Weasel as a function of time and altitude.

Figures VIII, IX, X and XI show activities in the context of physical space and time. Figure XII is a representation for showing activity in a cognitive or information space (Shalin & Jaques, 1997). This representation shows plans as boxes and goals for those plans as ovals. Figure XII shows the information processes involved in locating targets using information from the APR-38 Radar Attack and Warning System (RAWS) in the Wild Weasel. Three elements of the RAWS are involved. A PPI display is an egocentric (plane at the center) representation of the battle space. SAMs are represented as alphanumeric symbols. The location of these symbols indicates the bearing to the target. A digital display has two modes. In one mode, the range, radio frequency, pulses per second, and scan frequency are displayed. In the other mode, power, pulse width, scan duration, and scan type are displayed. A Panoramic display provides a graphical display of the radio frequency characteristics. The plan goal graph provides a very detailed description of information processing activities.

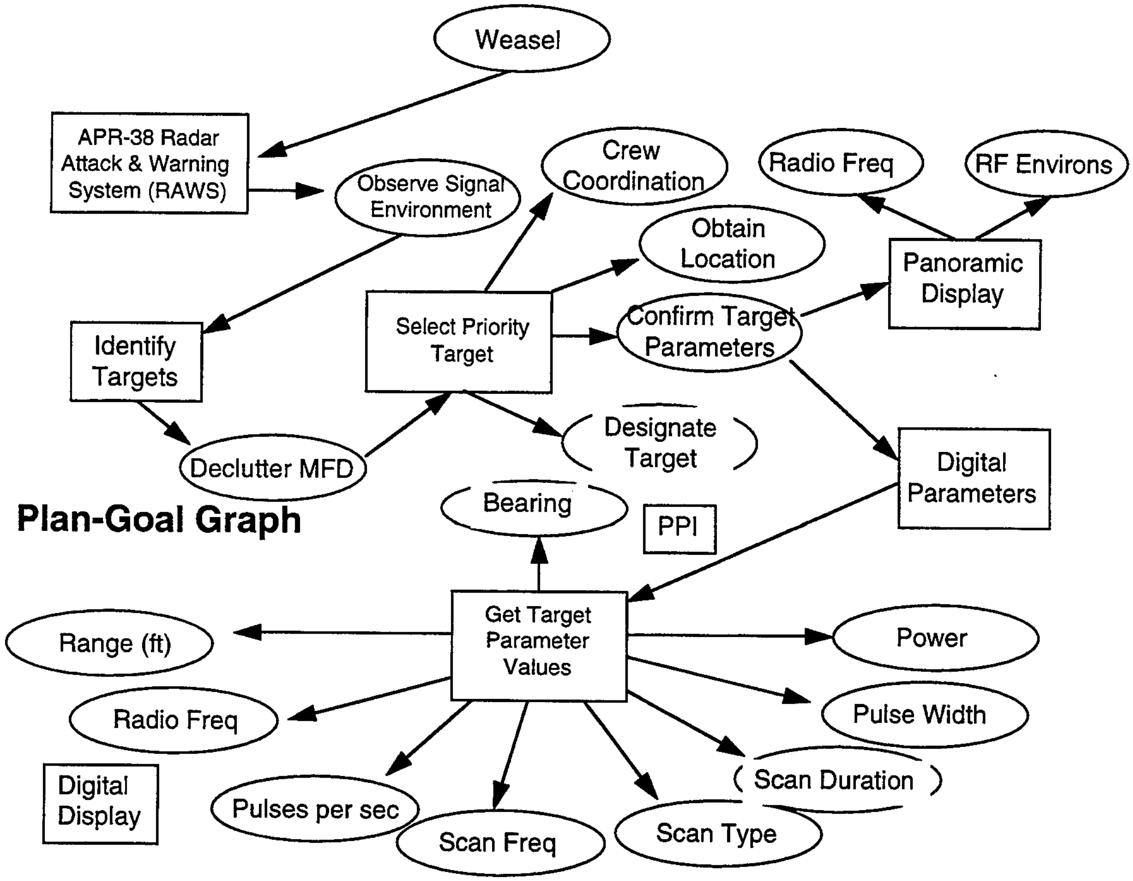


Figure XII. A plan goal graph showing information processing activities associated with using the APR-38 RAWS to identify targets and threats (Shalin & Jaques, 1997).

It is important to note that the "goals" in the plan goal graph are different than the goals discussed in Section II of this report. The goals in the plan-goal graph represent the goals for specific information processing activities. The activities in the plan goal graph are tightly constrained by the details of the interface that the operator is using. The mission goals reflect constraints at a much higher level of abstraction, such as military doctrine. Thus, these two types of goals differ in both level of decomposition and level of abstraction. For this reason, the goals discussed in Section II are not simply the sum of the goals represented in the plan-goal graph. Cognitive systems are nonlinear. It would be very difficult to discover military doctrine in the activities of the EWO processing information from the RAWS. Conversely, it would be difficult to predict the activities from a decomposition of military doctrine into smaller and smaller subgoals. The important point is that the view from above and the view from below provide different perspectives and offer different insight about the SEAD mission. It is not simply a matter of where you start your analysis. The analysis must proceed at all levels. No level is privileged. No level provides a comprehensive view. Complete understanding requires viewing the system from multiple perspectives. Figure XV attempts to emphasize the fact that levels along the diagonal of the analysis matrix provide different perspectives on the total work space. Activity analysis helps us to see what people do, but analyses at higher levels of abstraction are necessary to fully understand why people do what they do. Thus, it might not be possible to generate activities from decomposition of mission objectives or to derive mission objectives from integration of activities. Nevertheless, the activities should make sense in the context of the mission goals. The two perspectives should complement each other. If they don't, then that is an indication that there are problems at some level of analysis.

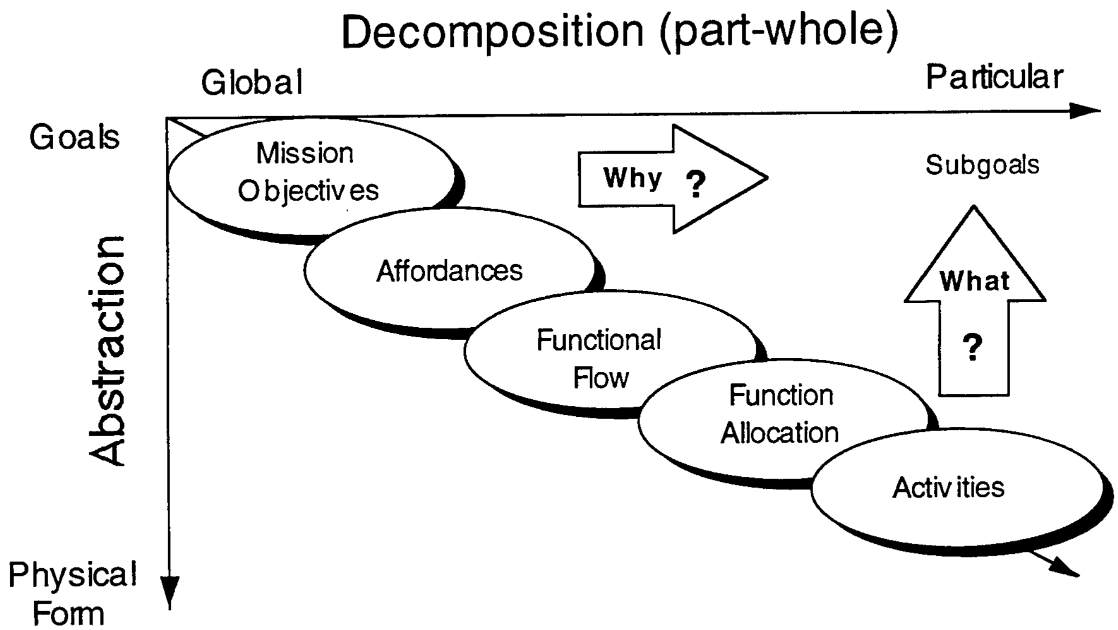


Figure XIII. This figure emphasizes that the "goals" in the plan-goal graph and the mission objectives discussed earlier reflect both different levels of decomposition and different levels of abstraction. These analyses provide qualitatively different insights into the cognitive system.

This has been just a small sample of the many kinds of representations that might be important to an activity analysis. There are many other possible representations. For example, detailed spatial layouts of controls and displays might be very important for an activity analysis. There is an enormous amount of information at the bottom of Rasmussen's pyramid. It would be impossible to capture every detail of the activity. Thus, the analyst must sample the population of activities wisely. Analyses at higher levels of abstraction can help to inform hypotheses about what details might be important and what details might be ignored. But the analyst has to be open to surprise and has to be prepared to assess and revise hypotheses that were formed from analyses at higher levels of abstraction.

Also, it is important to note that the activity level is the level where change is most dynamic. A small change in the design (e.g., configuration of a display or automation of a subfunction) can have radical consequences for work activities. In some respects, the higher levels of abstraction represent the givens of the design problem and the lower levels represent solution to the design problem. That is, design is to shape the activities to conform to the value systems that define the mission requirements.

In relation to the overall analysis framework (Figure I, Page 11), activity analysis reflects the confluence of a situation and awareness constraints. An activity represents a path through the SEAD problem space. This path might reflect the choices of a particular agent (7) in response to a particular sequence of events or might represent normative considerations with respect to a task situation (2), a decision task (3), or a mental strategy (4). Our ability to make sense of activities in light of analyses at higher levels of abstraction is an important test of our understanding of the system.

VII. SUMMARY AND DISCUSSION

Suppression of enemy air defenses --- as an agglomeration of high-technology weapons and apparatus, old and new tactics, and traditional forces and concepts --- engenders the same paradoxes that befell the tank, the airplane, the submarine of World War I, and nuclear weapons of World War II. Modern SEAD weapons and concepts arrived on the scene long before holistic patterns of use were developed for them. The impetus to develop SEAD weapons unwittingly brought about war-fighting technologies that had unforeseen consequences on the modern battlefield. SEAD weapons and tactics accelerated modern warfare's evolutionary process so much that traditional methods of determining effectiveness for SEAD no longer make much sense (Brungess, 1994, p. 51, emphasis added).

The goal of the cognitive task analysis outlined in this report is to frame general and specific design questions with respect to "holistic patterns of use." General issues include assessment of information and control requirements and hypotheses about function integration (Geddes, 1997). Specific questions include hypotheses about the most effective use of automation, the best representations to be used in displays, the type and format of controls, the structure of teams, the criterion for selecting personnel, and the structure of training programs.

What has been discovered in the process of this analysis? At the start of the analysis, the image of a SEAD mission was of a small team of aircraft attacking a SAM site. This image reflects an historical perspective grounded in the experiences from Vietnam. In this image, SEAD was defensive (reactive) and piecemeal. This image has greatly expanded as a result of this tabletop analysis. SEAD is now viewed in the context of broad Air Force Doctrine and in the larger context of electromagnetic warfare. SEAD has evolved. SEAD of the future will be more offensive (proactive) and will be an integral part of a highly coordinated effort directed at an integrated air defense system (IADS). This is the image that ought to be guiding the design of UCAVs. UCAVs should not be thought of as a replacement for the Wild Weasel---because, if that is the basis for design, then UCAVs will be obsolete before they are even fielded. UCAVs must be designed as integral components within a global strategy to disable IADS. The role of UAVs in the global strategy will include reconnaissance, jamming, deception, and weapons delivery.

Because of the secondary objective to illustrate the CSE approach, efforts were made to scale the work analysis to a manageable mission. For this reason, the image of a few planes attacking a few SAM missile sites was very attractive. It was difficult to let go of this image and that image still dominates sections of this analysis. However, this is the power of the cognitive systems approach---it forces the analyst to confront the larger context of work. From an engineering perspective, simplification of a problem can be a very powerful heuristic that allows the application of powerful analytic techniques. In the world of Henry Ford (who could proclaim that the customers could have what ever color they wanted as long as it was black), the design environment was such that the simplifying assumptions could be justified in practice. However, this is less true today. Projections based on linear logic (e.g., the prediction of the paperless office) do not reflect the reality of an information age where interactions dominate. This is especially true for a domain like electromagnetic warfare. We can't scale the problem to fit our methods. The methods must be scaled up to the problem. The problem of electromagnetic warfare is huge with significant interactions as a result of technological, economic, and political forces. The CSE approach is not going to simplify this problem--however, it is a formidable conceptual tool that might help the analyst to fully appreciate the nature of this complex work domain.

This report simply scratches the surface. It represents a preliminary tabletop analysis of the problem where most of the information was obtained from publications in general circulation. This tabletop analysis is an important first step in a continuing task analysis. The tabletop analysis provides access to "conventional wisdom" with respect to the SEAD mission. It helps to establish general dimensions of the problem space; to learn the appropriate vocabulary; and to identify the appropriate domain experts. A next logical step toward a more complete analysis would include interviews with domain experts.

VII. A Interviewing Domain Experts

Who are the domain experts? Classical approaches to cognitive task analysis have focused on the "users" of the system as the domain experts. This is due to the assumption that design should be to support the "mental models" of these users. However, a CSE approach is directed at the work space (not the space between any particular operator's ears) (See Vicente 1997). Certainly, users are one source of information about this space. However, the understanding of operators is often incomplete.

The people who might provide deeper insights into the SEAD mission include EWOs and pilots who have experience with the manned SEAD mission; experts on electromagnetic warfare and technology (including radar operators, image analysts, radar system designers, and engineers); experts on UAV technology (including UAV operators, UAV designers and engineers); experts on military strategy and tactics (including experts on IADS and experts on air superiority representing multiple service branches).

The interviews provide a check on our understanding of the "conventional wisdom." They also provide a first look at "conventional practice." In the past, cognitive task analyses have found that practice sometimes diverges from the conventional wisdom captured in text books. There are many possible reasons for this. Sometimes practice reflects contextual constraints not considered in the text book. Often, practice is ahead of conventional wisdom in adapting to changes that arise as a result of new technologies or as a result of changing economic or social climates. In addition, interviews also provide an opportunity to detect "unconventional wisdom." Unconventional wisdom reflects individual insights that are not well known, but that once expressed can be recognized by other experts as creative and innovative solutions. Finally, the interviews can be a source of "contradictions." Particularly with new technologies, there will be disagreements among experts. For example, there seems to be some disagreement in the published literature about the wisdom of replacing the Wild Weasel with aircraft armed with the HARM targeting system (HTS). The arguments among experts can provide important insights about the work domain.

VII.B Field Observations

In addition to talking to experts, it is also valuable to observe the work domain. Just as conventional wisdom and conventional practice may diverge, behavior may not always be consistent with verbal reports. There are many facets of expertise that are very difficult to articulate accurately. Thus, it is important to observe behavior in actual work settings. For the SEAD mission, particularly UCAV SEAD, observations in the actual domain are difficult (due to the breakout of peace and due to the fact that UCAVs are only at a conceptual stage of development). However, there are two environments where observations might be made. One environment is electronic combat exercises such as the Air Force's Green Flag and Cope Thunder. It could be very informative to follow one of these exercises from start to finish. A second environment is reconnaissance UAV operation. There are both training facilities and operational facilities where observations of UAV operators might be made.

VII. C Experimental Evaluation

Eventually, it may be important to test hypotheses derived from tabletop analysis, interviews, and observations in more controlled environments. These environments might include both low fidelity part task simulations and rich high fidelity simulations. The validity of these observations will depend critically on the ability to replicate meaningful chunks of the work domain in the laboratory. This reflects the iterative nature of the cognitive task analysis process. A goal of the analysis is to discover meaning within a work domain. These discoveries then become the basis for defining "high fidelity" for a simulator. Then, that simulator is used to evaluate hypothesis arising from the analysis. There is a clear danger here of confirmation bias. For this reason, it is important to iterate between the simulator and the operational environment. Ultimately, the analysis loop must be closed through the actual work domain. When inferences drawn in the simulator are inconsistent with observations in the operational environment this feedback must be used to improve the fidelity of the simulation.

VII. D Supporting Design

Ultimately the goal of the cognitive systems analysis is to support design. Thus, the products of that analysis should be useful to designers. For the most part, designers are unlikely to read a report such as this. Thus, it is important to develop alternative representations for the information and insights accumulated during the task analysis. In parallel with the development of this report, a tentative framework for a hypertext environment is being developed. This hypertext environment would be structured in a way that was consistent with the nested hierarchical structure of Rasmussen's abstraction hierarchy. The linking facilities of the hypertext format would be used to map across levels of the nested hierarchy to capture the semantic links. The hypertext document is called ICE---integrated constraint environment. The hypothesis is that the combination of a nested hierarchical structure and the hypertext links will provide a more effective representation than the narrative format of this document. In addition to text, the ICE environment would incorporate many different graphical representations within it (including functional flow diagrams, concept maps, plan goal graphs, time histories, interface schematics, etc).

Also, for complex systems, and particularly for competitive environments like electromagnetic combat, design is never complete. The system is constantly adapting in response to changing threat environments and technological innovations. Thus, the cognitive task analysis has to be a "living" analysis that can grow with the system as it evolves. The hypertext environment proposed for ICE will be designed to allow it to evolve to reflect deeper understandings of the work domain and evolutions within the work domain in response to new technologies and threats. The ICE program will be designed to be a living memory that captures the design rationale for the evolving system.

VII. E Summary

This report is a small first step to understanding the evolving SEAD work domain. The hope is that this first step will eventually lead to a deeper understanding of the SEAD mission. This deeper understanding may, in turn, guide the design and evaluation of UCAV technology so that it will be suited to the requirements of the SEAD mission. As the quote from Hancock (1996), which closes this report, emphasizes, we hope to eventually understand *how* UCAVs can work and *why* they may be useful (or not) for accomplishing the SEAD mission.

The report is also intended to illustrate the CSE approach to work analysis. Using the CSE framework, the SEAD mission was evaluated from multiple levels of abstraction and at different levels of decomposition. Although the current analysis is preliminary, hopefully the reader can begin to appreciate the scope and power of the cognitive systems approach for relating the causal (how) and the functional (why) questions that form the basis of any design problem.

> *Science and technology have always tried to answer the question "how?" How does this or that mechanism work? What are the laws and causal properties that underlie this phenomenon and, in the case of technologies, how can such knowledge be used to develop a useful tool or machine? However, science and technology rarely, if ever, address the question "Why?" It seems to be outside their respective universe of discourse. The question is ruled inadmissible or inappropriate for the methods and capabilities at hand. I reject this absolutely. I submit that questions of how and why are so mutually dependent that they should never be considered independently, and I attribute much of our present circumstance to this unfortunate and unhappy division. Those who know how must always ask why. Those who ask why must always think how. (Hancock, 1996)*

VIII REFERENCES

Air Force Manual 1-1 (1992). *Basic Aerospace Doctrine of the Air Force.* US Government Printing Office.

Bennett, K. B., Nagy, A. L., & Flach, J.M. (1997) Visual displays. In G. Salvendy (Ed.) *Handbook of human factors and ergonomics.* New York: Wiley.

Brungess, J. R. (1994). Setting the context: Suppression of enemy air defenses and joint war fighting in an uncertain world. Maxwell AFB, AL: Air University Press.

Clancy, T. (1995). *Fighter Wing.* New York: Berkeley Books.

Eggleston, R.G. (1987). The changing nature of the human-machine design problem: Implications for system design and development. (p. 113 - 125). In W. Rouse & K. Boff (eds.) *System Design: Behavioral perspectives on designers, tools, and organizations.* New York: North-Holland.

Eggleston, R.G. (1988). Machine intelligence and crew-vehicle interfaces. In E. Heer and H. Lum (Eds.), *Machine Intelligence and Autonomy for Aerospace Systems* (pp. 51-87). Washington, DC: American Institute of Aeronautics and Astronautics.

Eggleston, R.G. (1993). Cognitive interface considerations for intelligent cockpits. *Proceedings for Combat Automation for Airborne Weapons Systems: Man/Machine Interface Trends and Technologies* (pp. 21-1 to 21-16). Neuilly Sur Seine, France: NATO Advisory Group for Aerospace Research and Development. AGARD-CP-520, pp 21-1 - 21-16.

Fitts, P.M. (1962). Functions of men in complex systems. *Aerospace Engineering,* 21(1), 34 -39.

Fitts, Lt. Col. R.E. (1980). *The strategy of electromagnetic combat.* Los Altos, CA: Peninsula Publishing.

Flach, J.M. & Bennett, K.B. (1996). A theoretical framework for representational design. In R. Parasuraman & M. Mouloua (Eds.) *Automation and human performance.* Mahwah, NJ: Erlbaum.

Geddes, N. (1997). Associate systems: A framework for human-machine cooperation. (237 -242). In M.J. Smith, G. Salvendy, & R. Koubek (Eds.) *Design of Computing Systems: Social and Ergonomic Considerations.* Amsterdam: Elsevier.

Hancock, P.A. (1996). Teleology for technology. In R. Parasuraman & M. Mouloua (Eds.) *Automation and human performance.* Mahwah, NJ: Erlbaum.

Hewitt, W.A. (1993). *Planting the seeds of SEAD.* Maxwell AFB, AL: Air University Press.

Hutchins, E. (1995). *Cognition in the Wild.* Cambridge, MA: MIT Press.

Joint Pub 3-01.4 (1995). JTTP for Joint Suppression of Enemy Air Defenses (J-SEAD). July, Joint Chiefs of Staff.

Klein, G.A. (1993). A recognitioned-primed decision (RPD) model of rapid decision making. In G.A. Klein, J. Orasanu, R. Calderwood, & C.E. Zsambock (Eds.). *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Norman, D.A. (1988). *The psychology of everyday things.* New York: Basic Books.

North, D.W. (1997). U.S. Military weighs future of SEAD. *Aviation Week & Space Technology.* June 16, 151 -154.

Perrow, C. (1984). *Normal Accidents.* New York: Basic Books.

Rasmussen, J. (1986). Information processing and human-machine interaction: An approach to cognitive engineering. New York: North Holland.

Rasmussen, J. (1998). Ecological interface design for complex systems: An example: SEAD - UAV systems. Interim Report EOARD - Contract: F61708-97-W0211.

Rasmussen, J., Pejtersen, A.M. & Goodstein, L.P. (1994). *Cognitive Systems Engineering.* New York: Wiley.

Rasmussen, J. & Vicente, K.J. (1989). Coping with human errors through system design: Implications for ecological interface design. *International Journal of Man-Machine Studies,* 31, 517 - 534.

Rochlin, G.I., LaPorte, T.R., & Roberts, K.H. (1987). The Self-Designing High-Reliability System: Aircraft Carrier Flight Operations at Sea. *Naval War College Review,* Autumn.

Shalin, V. & Jaques, P. (1997). Presentation to the UAV working group at Wright State University. Dayton, OH. (Sept).

Shaw, R.L. (1985). *Fighter Combat: Tactics and Maneuvering.* Annapolis, MD: Naval Institute Press.

Sweetman, B. (1997). Fighters without pilots. *Popular Science,* November, 95 - 101.

Trussel, R. (1997). A SEAD story. Unpublished manuscript.

Vicente, K. (1992). Memory recall in a process control system: A measure of expertise and display effectiveness. *Memory & Cognition,* 20, 356 - 373.

Vicente, K. (1997). Should an interface always match the operator's mental model? *CSERIAC Gateway,* VIII(1), 1 -5.

Whitaker, R. & Kuperman, G. (1996). Cognitive engineering for information dominance: A human factors perspective. AL/CF-TR-1996-0159.

Woods, D.D. (1991). The cognitive engineering of problem representations. In G.R.S. Weir & J. L. Alty (Eds.), *Human computer interaction and complex systems.* London: Academic Press.

Woods, D.D. Johannesesn, L.J., Cook, R.I., & Sarter, N.B. (1994). Behind human error: Cognitive systems, computers, and hindsight. State of the Art Report (SOAR). CSERIAC: Wright-Patterson AFB, OH.

Worch, P., Borky, Gabriel, Heiser, Swalm, & Wong (1996). UAV Technologies and Combat Operations, (SAB-TR-96-01). Department of the Air Force, AF/SB Washington, DC.

Worch, P. (1997). SEAD mission profile. Presentation at Workshop on Human Machine Issues in UAVs. George Mason University, Fairfax, VA. (Oct).