Title: A Hybrid Approach to Cognitive Engineering: Supporting Development of a Revolutionary Warfighter-Centered Command and Control System

Associated conference topic: Decision-making and Cognitive Analysis

Authors:
Jennifer Ockerman
Jennifer.ockerman@jhuapl.edu

Jennifer A.B. McKneely
Jennifer.mckneely@jhuapl.edu

Nathan Koterba
Nathan.koterba@jhuapl.edu

Point Of Contact :
Jennifer A.B. McKneely

Johns Hopkins University/Applied Physics Laboratory
11100 Johns Hopkins Rd
Laurel, MD 20723

240 228-7476 (phone)
240 228-6668 (fax)

Jennifer Ockerman, PhD, Jennifer McKneely, and Nathan Koterba
Johns Hopkins University, Applied Physics Laboratory

Effects-based Decision Analysis Methodology (EDAM): Designing Revolutionary Command and Control Systems

ABSTRACT

Traditional cognitive engineering approaches do not adequately address the breadth of human performance issues in revolutionary Command and Control (C2) systems. Consequently, a best-practices approach has been developed. This paper describes an integrated cognitive engineering approach—the Effects-based Decision Analysis Methodology (EDAM)—for the requirements analysis and design of revolutionary command and control systems and domains. This hybrid approach uses knowledge elicitation and representation techniques from several current cognitive engineering methodologies. The techniques were chosen to allow for decision analysis in the absence of an existing similar system or domain. EDAM focuses on the likely system or domain constraints and the decisions required within that structure independent of technology, existing or planned.

INTRODUCTION

Every new system design falls along a continuum of change, from minor change to evolutionary change to revolutionary change. As shown in FIGURE 1, minor change involves alterations to a system's front-end or human interface but no substantial change to the back-end system and no change to the existing work organization. Evolutionary change involves substantial alterations to both the front- and back-end of the system but no substantial change to the work organization. Revolutionary change involves substantial alterations to the work organization which necessitates entirely new front- and back-end system components. Regardless of the amount of change, any design effort benefits tremendously from a thorough needs analysis, which includes human performance assessments and helps develop system requirements.

Many methods exist that can determine the requirements for systems undergoing minor changes. These methods focus on understanding the current tasks and work processes in order to improve the operator interface to support those tasks. A few methods were developed and are promoted for evolutionary change. These methods focus on the goals, decisions, and constraints of the existing system or domain in order to understand how best to control and/or interact with the existing system or domain. No widespread methods exist, however, that address human performance in complex systems undergoing revolutionary change. Developing such methods for revolutionary systems is difficult because no current work organization exists for analysis. As a result, designing new revolutionary systems is also difficult.

As the Department of Defense moves towards a net-centric paradigm, new revolutionary command and control (C2) systems and work organizations are necessary. In order to design systems for and support development of this net-centric framework, JHU/APL has developed an integrated cognitive engineering approach. Current individual cognitive engineering methodologies only partially capture the multiple factors affecting humans and their performance in C2 work organizations and primarily focus on minor change and evolutionary designs, not revolutionary designs. The JHU/APL integrated methodology considers the operating environment, collaboration between humans and machines, user goals, operator decision methods and styles, battle rhythm dynamics, multi-level security, cognitive strengths and limitations and physiological factors, such as stress and fatigue, for a revolutionary new design.

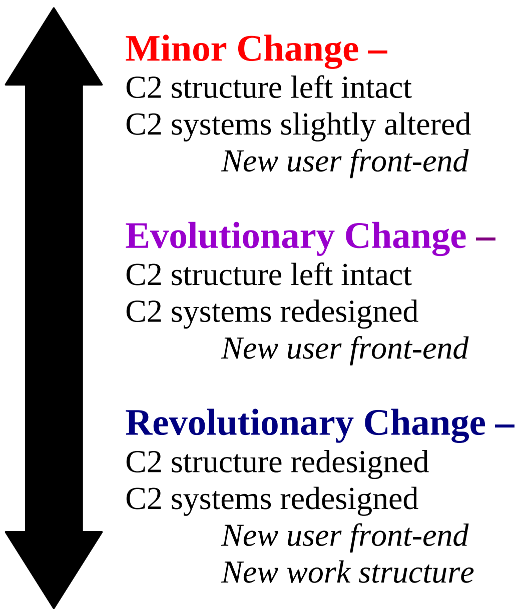


FIGURE 1 Change Continuum

The Effects-based Decision Analysis Methodology (EDAM) employs various knowledge elicitation and representation techniques from current cognitive engineering methodologies. EDAM is intended to be used throughout the design and development of a prototype. Information gathered with EDAM will also be used throughout the project to evaluate human performance in the proposed system. Although EDAM was developed to aid in the design of revolutionary systems, it may be applied to systems undergoing minor and evolutionary changes.

COGNITIVE ENGINEERING AND EDAM

The goal of cognitive engineering is to provide optimal interoperability between human operators and today's complex systems so that human operators can more effectively perform their duties and overall system performance improves. This goal is particularly important for Command and Control (C2) design where warfighters use information from various sources to make critical decisions in the planning and execution of strategic, operational, and tactical goals. Understanding user goals and decisions is critical in ensuring that the total system provides utility.

In addition to the goals (i.e., desired effects) of warfighters and the decisions required to meet those goals, the nature of the operating environment is a major component to operational success. Because multiple factors affect the human component of C2 performance, a new methodology employing the best practices from current cognitive engineering processes is required. This method brings together analyses and techniques from Scenario Based Design, Situation Awareness Analysis, Cognitive Task Analysis, Team Cognitive Task Analysis, Cognitive Work Analysis, Use Cases and Storyboarding.

EDAM (see FIGURE 2) begins with the fundamentals: scenario design/articulation and an initial work domain creation. These fundamentals lead into a knowledge elicitation phase of mission functions. The knowledge elicitation is conducted on two parallel paths addressing cognitive performance, one focusing on decisions and the other on the work environment. Knowledge elicitation involves various activities, from attending function related courses and visiting training sites, command centers, and other C2 intensive sites to interviewing subject matter experts (SMEs) with semi-structured and structured techniques. The two paths converge on decision and work environment analysis, which involves producing various representations of the knowledge elicited. The analysis and the resulting representations lead to decision support system (DSS) design concepts. The DSS design concepts can now be combined with technology assessments to create a total system design concept and, ultimately, a demonstrable prototype. Note that although these steps are listed as a sequence, concurrent and iterative work will take place throughout the methodology. Furthermore, the methodology is best applied by a multi-disciplinary team that provides systems, human performance, software, hardware, and operational/domain views into the design effort.

Throughout the design effort, human performance assessment is conducted to the degree possible. Initially, assessment occurs through paper-based modeling and simulation to understand workload, support function allocation and organization design decisions. Later in the design process, human-in-the-loop assessments of design concepts and the prototyped demonstrator provides performance evaluations. Throughout the design and development process, SME participation is critical. Domain knowledgeable individuals assist in developing the scenarios that are used for interviews with current warfighters to elicit decision and work environment requirements, and SMEs participate in design evaluations.

Familiarization of the existing domain and job environment is extremely important for all team members. In particular, EDAM team members review or study relevant material, such as work process documentation (e.g., Tactics, Techniques and Procedures (TTPs), Doctrine), training packages, and operational requirements; participate in training; and observe operations and exercises.

The following sections describe in detail each of the steps discussed above. In addition, potential products from each step are presented.

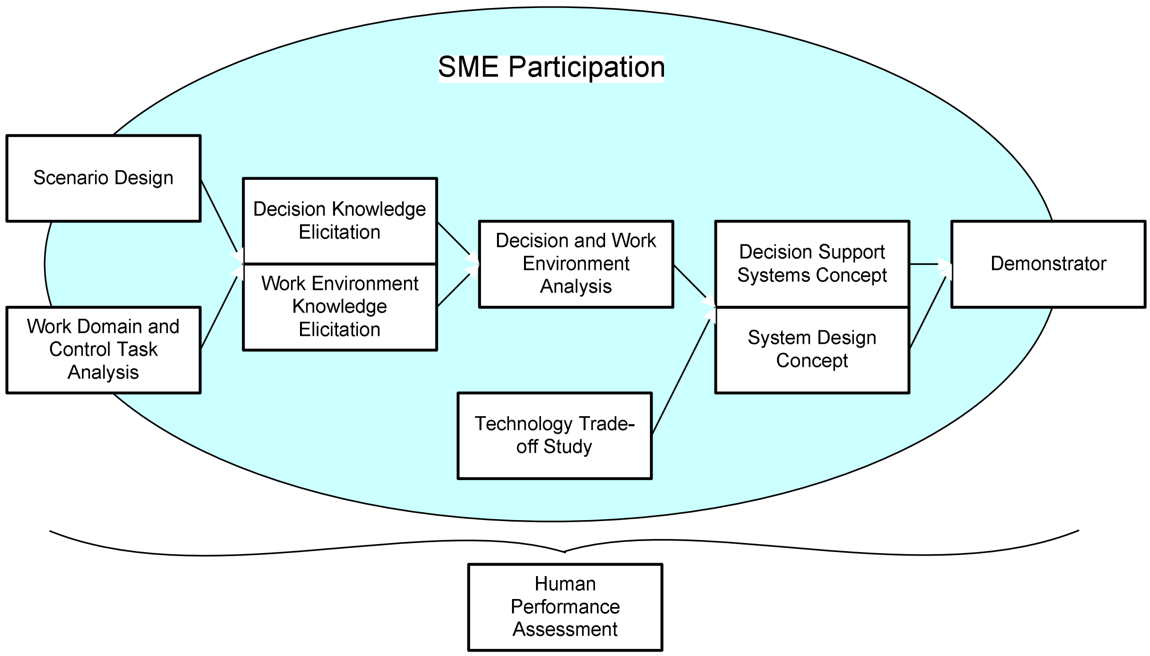
EDAM COMPONENTS

Scenarios

C2 operations involve many complex functions. To fully understand the effects/goals that support mission accomplishment, C2 must be assessed in context. Since revolutionary designs do not offer an existing system and work organization to analyze, EDAM calls for developing one or more operation scenarios to provide that context. SMEs aid in the development and validation of the scenarios. The EDAM process identifies scenario specificity requirements, and domain experts help to ensure realism. The scenarios, depicted in textual and graphic format, are used during the knowledge elicitation phase to structure the interview process.

In addition to initial knowledge elicitation, the scenarios are used at all stages of the EDAM process to provide context. As such, it is important that warfighter SME interviews are structured to enhance and update the scenarios' descriptions, logical essentials (e.g., information requirements), and process steps to reflect reality and the new C2 environment.

EDAM's use of scenarios is based on the cognitive engineering approach scenario-based design (McGraw and Harbison, 1997). The primary benefits of scenario-based engineering – to bring developers and process engineers together (in our case cognitive process engineers) in a structured environment – are leveraged in the EDAM process. The focus on scenarios helps to ensure that all of those involved in the design development are working within a realistic context.


SME Participation
Scenario Design
Work Domain and Control Task Analysis
Decision Knowledge Elicitation
Work Environment Knowledge Elicitation
Decision and Work Environment Analysis
Decision Support Systems Concept
System Design Concept
Technology Trade-off Study
Demonstrator
Human Performance Assessment

abstraction hierarchy can also be decomposed into various levels of subsystems called a decomposition. The decomposition is generally represented from left to right with the whole system at the left and subsequent subsystems to the right.

	Whole System	Sub-system A	Sub-system B
Functional Purpose/Goal			
Abstract Function			
Generalized Function			
Physical Function			
Physical Form			

FIGURE 3 Work Domain Analysis Result - Abstraction Hierarchy

The control task analysis is generally represented with multiple decision ladders; a generic decision ladder is shown below (see FIGURE 4). A decision ladder is not constrained by who (either human operator or machine operator) is controlling or interacting with the domain or system.

Eventually, the results of the work domain and control task analyses leads to the development of a function allocation, initial user profiles, and machine capabilities. For future C2 systems, manning organizations are difficult to base on an evolution of current manning structures. Instead, the EDAM approach identifies the required functionality and the requisite knowledge, skills, and abilities (KSAs) required to perform those functions. Once the required KSAs are identified, functions can be aggregated into roles; these roles will provide a framework for developing the initial user profiles. Throughout the EDAM process, the initial functional allocation is assessed for workload impacts and decision/task reassignments, and user profiles are refined.

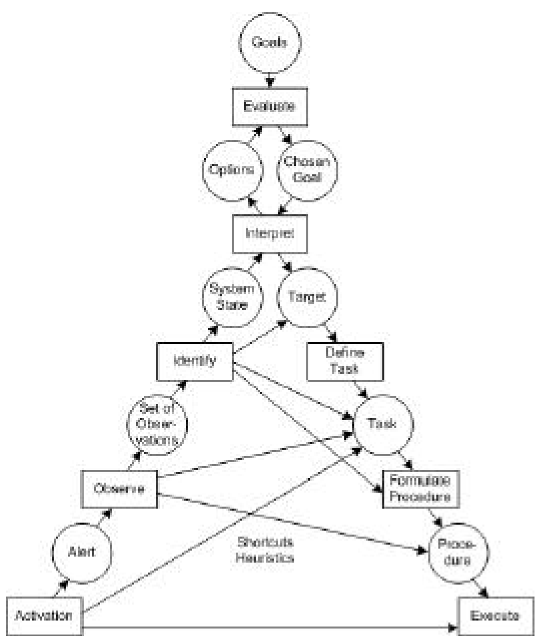


FIGURE 4 Control Task Analysis Result - Decision Ladder

Decision Knowledge Elicitation

To refine and authenticate the information gleaned from the available documentation, interviews with SMEs are performed. The decision knowledge elicitation focuses on the goals that support the mission, the decisions necessary to achieve those goals, and the information requirements and strategies used for each decision, based on a Goal-Directed Task Analysis (GDTA) (Endsley, 2003). During semi-structured interviews, the EDAM team walks SMEs through the developed scenarios. (Note: While individual interviews are ideal, schedule and resource limitations may require group interviews. In this case, the elicitation activity resembles more of a workshop/roundtable approach than an interview).

This analysis captures user goals and corresponding decisions, yielding situational assessment and actionable information requirements. This information is represented as shown in FIGURE 5. In addition to a combined list of decisions made, actionable information needed to make such decisions, and the interactions and information flow among decisions emerge. This information/decision flow data is best represented by flow charts.

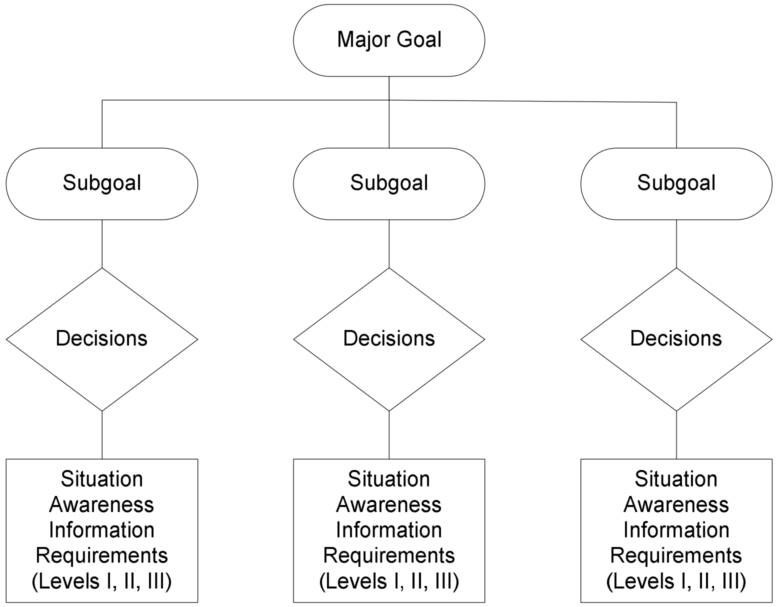


FIGURE 5 Goal-Directed Task Analysis Output

To provide more detailed decision analysis, the EDAM team also conducts a Cognitive Task Analysis (CTA). Several methods for conducting CTAs exist. One method, based on the work of Gary Klein (Crandall, B., Klein, G., Militello, L., & Wolf, S., 1994), is the knowledge audit. A knowledge audit consists of interviews with SMEs to mine their expertise. The SME is queried on the actions he/she would take at each decision point. Complex decisions are examined in more depth to focus on the factors that contribute to expertise (e.g., cues and strategies used). This information can aid in designing systems that help novice operators perform more like experts despite their lack of experience. It can also provide information regarding personnel and training needs.

As there is no existing system or domain, scenario-based techniques are applied; the tactically-realistic scenarios developed and validated previously are used to walk-through the questions to elicit decision making requirements. The table below provides an example used to elicit high level decisions and accompanying requirements for an Air Force Combined Air and Space Operations Center time sensitive targeting system.

Work Environment Knowledge Elicitation

Conducted concurrently with the GDTA and CTA described above, the Work Environment Knowledge Elicitation creates a representation of the physical work environment and organizational structure. In addition to the actual tasks and decisions, the environment and organization also impacts the work that is accomplished. This information is collected through field observation and ethnographic studies, which involve observing actual C2 operations, exercises, and/or training to understand and accurately document the current operational process, strategies, and tools. The following activities are conducted to ensure useful and complete knowledge is gained from the observations:

a. Review doctrine prior to exercise with C2 representatives and trainers to identify holes in doctrine. Observe exercise(s) and document divergence from doctrine and established processes.
b. Collect data passed to/from operator/supervisor, observe use of data and by whom, observe method/tool used to pass and process data, document cognitive decision-making process used by operator/supervisor (may require post-hoc discussions).
c. Conduct post exercise interviews with participants, including: conducting knowledge audit; documenting rationale for divergence, difficult aspects/events in exercise, paths of communication used and alternatives not employed, heuristics and experiential knowledge

and how that is applied to situation at hand; reviewing errors; collecting strategies, tools, communication channels, communication flow not observed but used in exercise (will require post-hoc discussions).

d. Assess usability issues associated with systems used in exercise (questionnaire, subjective evaluations).

e. Determine task frequencies and durations, task fragmentation/interruptions, fatigue and stress, and performance requirements.

TABLE 1 Example questions for decision knowledge elicitation

Probe	Questions to ask if SME is having a hard time identifying decisions/information requirements
Goals • What are your specific goals at this time? • How did you prioritize these goals? Are there conflicts? • How does the outcome of a particular goal influence the success of your prioritization/re-prioritization of other goals?	• Does this scenario fit a standard or typical scenario? • Did this scenario remind you of any previous case or experience?
Decisions • In this event in the scenario, what are the key decisions you are making?	• What decisions would you actually make? • What would cause you to make a decision at the time the decision was made? • What decisions would be considered but would be deferred and why? • Would any decisions be made in collaboration with other CAOC staff? • Would any decisions made require review and approval from other CAOC/TCT staff?
Information Requirements • In this situation, how would you go about making the required decisions, what would cue you? • What information would you seek? • Can you get this information? Is it currently available? • Who would you interact with? • What ambiguities would you try to resolve?	• How do you communicate with external teams (i.e., SOF), particularly in event 3? • How do you combine information (use specifics) to aid in decision making?
Errors • What types of errors are likely at this point? In this decision? • What makes this difficult?	
Situation Awareness – ability to respond • How do you maintain SA, what are you looking for, where does it come from (who are you talking to, what displays/systems do you use)?	• Who are you talking to, what displays/systems do you use?
Response • What is the effect of the decision? To whom are you providing information and action cues? • Who needs to know your decisions, information generated?	

Decision and Work Environment Analysis

Throughout, and after the completion of, the knowledge elicitation phase, the data and information collected are analyzed and represented in various ways. When designing revolutionary C2 systems, the EDAM team focuses the representations on high level abstract functions, goals and decisions and not on current practices and policies. A representation that integrates several types of information into one diagram is an operational sequence and activity diagram, which provides a graphical process flow divided across the different human and machine roles over time. An example is shown in FIGURE 7.

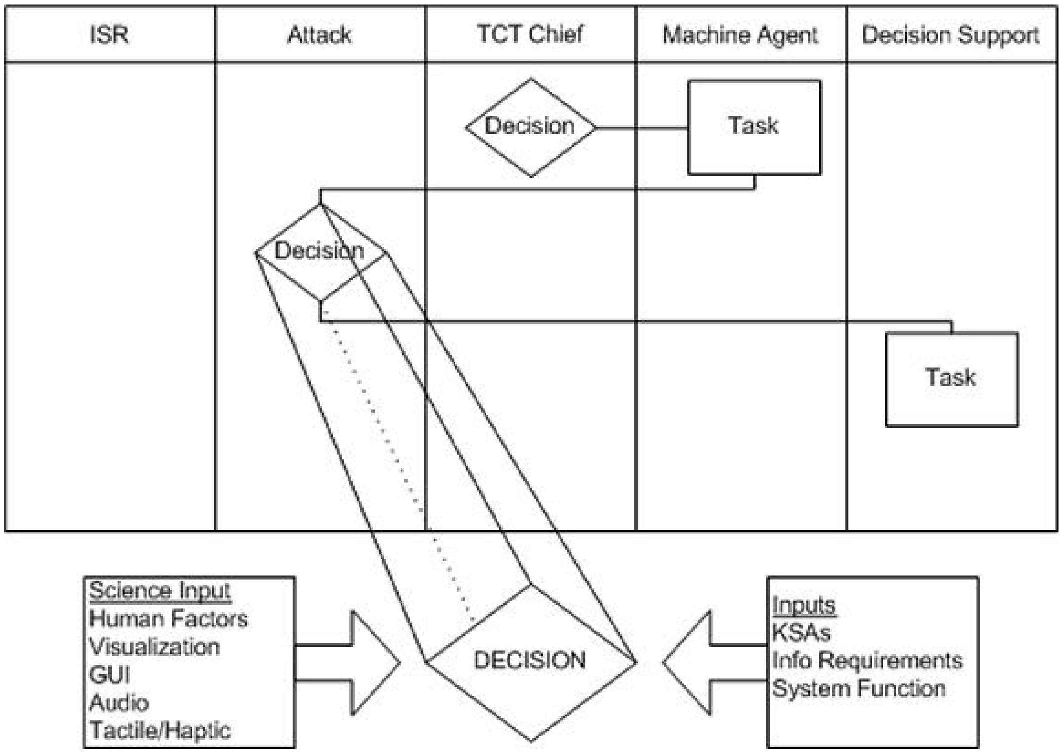


FIGURE 7 Example of Operational Sequence and Activity Diagram

In addition, a function allocation matrix is produced. This matrix matches the domain functions to various human and machine roles. An example is shown in FIGURE 8. Both of these representations accompany all the representations developed in previous stages to show a clear picture of the many aspects that affect work completed within the C2 system.

	Function 1	Function 2	Function 3	....
Human 1	X		X	
Human 2		X		
Agent 1			X	X
Agent 2			X	
....				

FIGURE 8 Example of Generic Function Allocation Matrix

Decision Support Systems Design Concept

This phase of EDAM specifies and develops operational aspects of the design – what the system does, and how the user interacts with it. In addition, it identifies system states that need to be revealed to the user, makes clear what user actions are available, and generates system responses that need to be presented through a graphical user interface (GUI).

The knowledge from the previously described knowledge representations is now transferred into formats that the software development team can use to produce a prototype demonstration system. Translating the results of the Decision and Work Environment Analysis into a form that software developers can use has been a weak link in traditional cognitive engineering efforts. To bridge this gap, the EDAM embraces unified modeling language (UML) techniques to create use cases and activity diagrams. Standard development representations are also created, including annotated story boards (paper prototypes which demonstrate the graphics, interactions, and navigation of the proposed GUI).

Employing these software development-focused techniques eases the transition from the initial EDAM products to a prototype that software developers can implement. Moreover, this process is not isolated from the developers and systems engineers and is tied closely to the total System Design Concept phase described below. All previously described knowledge representations are also available to the developers and systems engineers. Furthermore, representatives from these teams are encouraged to participate in all interactions with C2 representatives and SMEs.

Technology Trade-Off Study

The software development team leads technology trade-off studies. The technology trade-off study determines the best hardware and software configuration for developing and presenting a prototype demonstrator. Throughout the study, the EDAM team assists by providing expertise in human factors, usability, and supportability concerning warfighter C2 decisions-making issues.

System Design Concept

The total system design concept defines the system's physical work environment, organizational structure, policies, and hardware. When revolutionary systems are developed using EDAM, it is anticipated that changes and reduction in the organizational structure will also occur, which, in turn, may require changes in operational policies. In addition, the hardware used and the work environment are likely to differ dramatically from what is currently used.

To better understand the organizational structure and role changes that will best meet the needs of the new work domain design, the EDAM team conducts workload analyses using modeling and simulation to examine different task configurations among the personnel. This modeling and simulation may be conducted in Micro Saint Sharp or other discrete event simulation tools.

Furthermore, anthropometric considerations need to be reviewed. The design should utilize hardware that adapts adequately to varying personnel sizes and builds. Recommendations are documented and incorporated into overall system, GUI, and user interface designs.

As described previously, the System Design Concept phase occurs in conjunction with the Decision Support System Design Concept phase, and the new operational policies are incorporated into use cases, activity diagrams, and annotated storyboards. In addition, the EDAM team produces graphics (e.g., layouts, hardware designs, images, etc.) of the hardware and work environment configuration, including diagrams of the information flow and magnitude into, through, and out of the C2 system.

Prototype

Various methods of prototyping exist, ranging from paper sketches to full working systems. EDAM encompasses the earliest types of prototypes: storyboarding and requirements animation. These prototypes are used to communicate design guidelines to the software development team as well as to support human performance assessments, cognitive walkthroughs, and usability tests with C2 representatives. Storyboarding is normally a paper prototype while requirements animation is a dynamic representation but not a working system. The software development team continues to refine the prototypes by developing higher fidelity prototypes, including rapid prototypes which can be used to determine the adequacy of the design but do not themselves evolve into a final solution, incremental prototyping which builds the system in phases adding features over time, and evolutionary prototyping which uses evaluation and iteration to refine the prototype into a final demonstration system. The EDAM team supports the software development team's prototype development by providing expertise on how to meet the human decision making requirements within the system.

Human Performance Assessment

EDAM incorporates human performance assessments throughout the design process to validate analyses conducted, requirements derived, and designs developed. This performance assessment is based on modeling and simulation that evolves from sparse scenarios through detailed paper prototypes. The human performance assessment continues through the software development team's prototypes as well.

Metrics that are appropriate for a particular system should be developed as the design is being developed, but a short list of generic metrics includes: successful completion of tasks, time to complete a specified task by a specified user, percent of task completed, time spent on errors, number of errors per task, number of commands used to accomplish task, frequency of and time spent on help or documentation use, number of runs of success and of failure, number of available commands not invoked, number of regressive behaviors, number of time users need to work around a problem, and subjective user evaluations. These metrics are associated with performance goals and are evaluated throughout the EDAM and development processes.

CONCLUSION

Warfighters using today's C2 systems make numerous critical, time constrained decisions requiring a large amount of information. However, large screens inundated with data, legacy systems with limited interoperability, and poorly designed operator-machine interfaces force the warfighter to spend more time interacting with systems, analyzing information, and developing situational awareness than making critical decisions. Effective military operations are enabled by a system centered around human perception, understanding, abilities, and decision making, providing actionable information at the appropriate time, situation awareness through the display of knowledge (not data), and natural, intuitive interaction technologies. In short, future warfighters need the right information, at the right time, in the right modality.

Revolutionary C2 systems that provide decision support tools and a work environment that support rapid, accurate decision-making benefit from the application of warfighter-centered design approaches. Current cognitive engineering methods don't have the breadth required to adequately address the human performance considerations from organizational and work environment to the low-level detailed aspects of complex decision-making that can be codified into automation and decision support. Applying a hybrid approach, like EDAM, can help ensure that new C2 systems meet user performance requirements. Consideration of the operating environment, collaboration between humans and machines, user goals, operator decision methods and styles, battle rhythm dynamics, multi-level security, cognitive strengths and limitations and physiological factors, such as stress and fatigue, all of which are addressed and incorporated into design solutions.

REFERENCES

Crandall, B., Klein, G., Militello, L., & Wolf, S. (1994). *Tools for applied cognitive task analysis.* (Technical Report prepared Contract No. N66001-94-C-7008 for the Naval Personnel Research and Development Center, San Diego, CA). Fairborn, OH: Klein Associates Inc.

Endsley, M.R., Bolte, B., Jones, D.G. (2003). *Designing for Situation Awareness: An Approach to User-Centered Design.* New York, NY: Taylor & Francis Group.

McGraw, K. and Harbison, K. (1997). *User Centered Requirements: The Scenario-Based Engineering Process*. Mahwah, NJ: Lawrence Erlbaum Associates.

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

Vicente, K.J. (1999). *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jennifer Ockerman, Ph.D. *is recently employed as a senior cognitive systems engineer at Johns Hopkins University Applied Physics Laboratory where she has provided cognitive engineering expertise to various Department of Defense projects and homeland security and C2 of the future initiatives. Dr. Ockerman received a B.S. in Industrial Engineering and Operations Research from Virginia Tech and both an M.S. and Ph.D. in Industrial and Systems Engineering with a specialty in Human Integrated Systems and a minor in Cognitive Science from Georgia Tech. She has over 45 publications in the area of cognitive engineering.*

Jennifer A.B. McKneely *is a Senior Scientist at the Johns Hopkins University Applied Physics Laboratory where she is supporting the DD(X) program and coordinates Human Systems Integration related efforts including Tactical Tomahawk, Air Force Command Air Operations, Undersea Warfare, and Human-Autonomy R&D. Ms. McKneely has a background in human engineering, with a master's degree from George Mason University in Human Factors Psychology. As an employee of the Naval Surface Warfare Center Dahlgren Division, she has supported the redesign of the Naval Space Command Operations Center. She developed and led the human engineering task for the Theater Air Defense Area Air Defense Commander System. She developed a human engineering process that is published in the International Human Factors and Ergonomics Encyclopedia and was leveraged to support the development of the IEEE 1220 Systems Engineering standard. She led the DD 21 Manning/Human Systems Integration Team.*

Nathan Koterba *participates in task analysis, cognitive task analysis, ConOps Development, modeling/simulation, and GUI development for the Air Force and Navy at the Johns Hopkins University Applied Physics Laboratory. His current interests include software design, human systems integration, and human computer interaction. He received his B.S. in Computer Engineering at the University of Maryland, College Park in 2004.*