Command and Control Systems Engineering: Integrating Rapid Prototyping and Cognitive Engineering

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The study of systems engineering and its applicability to command and control (C2) systems reveals that the basic models support incremental development of multiple systems that necessarily will be integrated into a holistic C2 system. As the battle space for C2 has grown more complex, technology is necessary to enable the human to understand the battle space, plan successful courses of action to achieve desired military goals, monitor the tactical/operational environment, and react to any situation or threat that may interfere with achieving the commander's intent and guidance. To enable commanders and their staffs to achieve effective and efficient work processes, C2 systems must be well designed. A fully holistic approach to systems engineering will help ensure that a C2 system is well designed. Combining rapid prototyping with cognitive engineering is one way to achieve a more holistic view of the system. This article describes each of these disciplines and shows how the combination of these varied approaches may provide a key to good systems engineering practices in C2 systems.

INTRODUCTION

From the inception of Tactical Decision Aids in the military, there has been great debate over whether command and control (C2) is an art or a science. We have no desire to engage further in this debate, and we readily stipulate that whenever a human has ultimate control of the final decision on an appropriate course of action (COA), a certain art form is involved. But along with this stipulation, this article postulates that, because the battle space has grown more complex, technology is necessary to enable the human to understand the battle space, plan successful COAs to achieve desired military goals, monitor the tactical/operational environment, and react to any situation or threat that may interfere with the achievement of the commander's intent and guidance. Furthermore, we find it axiomatic, on the basis of years of observation, that commanders and their staffs working with well designed C2 systems are more effective at achieving their desired purposes; inversely, commanders who are forced to operate with poorly designed C2 systems are at times challenged to meet their objectives by the very systems designed to help them.

An unfortunate consequence of the art-versus-science debate for C2 is the lack of standardized systems engineering practices for systems developed to provide decision-making assistance to warfighters. Every engineer dedicated to providing systems to support C2 wants to build the appropriate tool set to enable warfighters to maximize their effectiveness. With the same vehemence as those who debate C2 systems' usefulness, the engineering community has itself debated the methods to gauge and test the effectiveness of these systems. Two distinct camps squared off in these debates. On one hand, the human factors engineering community has worked diligently to dissect the concepts of command and to determine what content and presentation of information is necessary to facilitate good decisions. This research has involved both physical and cognitive studies of commanders in controlled environments. On the other hand, many C2 developers have employed rapid prototyping in an "expert systems" approach, developing knowledge and heuristics by interviewing recognized experts, then codifying these rules into their systems and rapidly getting those systems into operational environments to determine how to best serve the warfighter. Each of these two camps desires the same end result: a better science of control to aid the art of command. This article is an attempt by two authors, each representing one of these camps, to show how the combination of these varied approaches may provide a key to good systems engineering practices in C2 systems.

As a way of describing the combined C2 systems engineering methodology, we first address and familiarize the reader with each approach used in isolation. These discussions include the systems engineering activities involved, as well as the associated strengths and weaknesses of the individual approach. Then we turn to a case study of a combined rapid prototyping and human factors approach. We hope to show the benefits of a combined human factors engineering and rapid prototyping approach to provide a more holistic systems engineering methodology for C2.

WHAT IS C2?

Joint Publication 1-02 defines C2 as follows:

> The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission.[1]

Significant work has been undertaken to model the necessary tasks performed by both human and machine functions for effective C2. One groundbreaking effort was that of Colonel John R. Boyd, U.S. Air Force (retired),[2] who created the OODA (observe, orient, decide, and act) loop model (Fig. 1) for air-to-air conflict. This model describes C2 as the need for the pilot to observe, orient, decide, and act.

Later models such as MAPE (monitor, assess, plan, and execute) and MAAPPER (monitor, analyze, assess, predict, plan, execute, and report) were subsequently developed to more specifically apply a C2 model to a larger theater of warfare and to more accurately describe that theater's processes of operation.

Paul North and Steven Forsythe[3] compared these models in their paper, "A Process Decomposition Approach for Evaluating Command and Control (C2) Functional Performance," and ultimately determined that three key elements (KEs) can be synthesized from each of these models. These KEs are (*i*) the need for the commander to maintain situational awareness, (*ii*) the need for the command staff to plan, and (*iii*) the need to execute or prosecute the warfighting mission. To fully account for the factors of C2, these KEs should be expanded to include a fourth element: (*iv*) the need to perform an accurate intelligence preparation of the battle space, as shown in Fig. 2. An accurate intelligence preparation of the battle space is what initiates the shared perspectives of the other three KEs and lays the foundation for all of the commander's decisions. Clearly, these four elements or tasks can be decomposed in many different ways, depending on the size of the warfighting theater and the specific mission being addressed by the command staff. However, if a commander is able

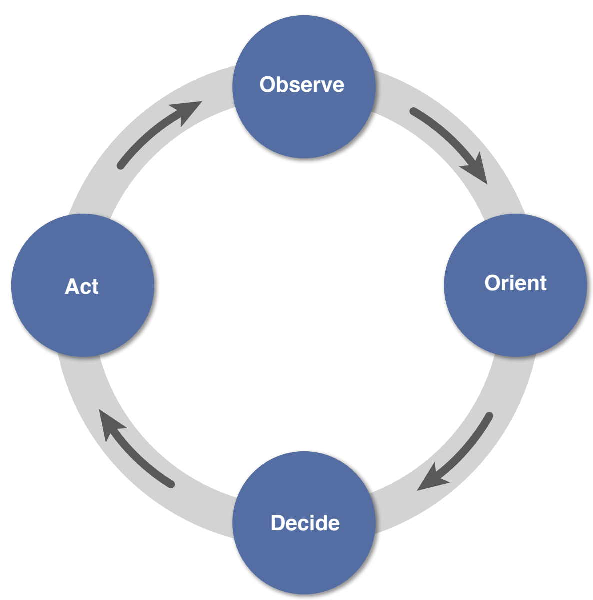

Figure 1. Boyd's[2] OODA loop model for C2.

Figure 2. Four KEs of C2.[3]

to understand the battlefield, plan numerous COAs to combat the enemy, monitor the battlefield and maintain situational understanding, and identify the threats to success and execute against those threats, that commander will have the ability to prosecute the mission to the full extent of his or her intent and guidance.

As technology has improved, there has been a shift in the proportion of C2 functions allocated to equipment (computers, displays, communications gear, etc.) versus those functions remaining with the experienced commander. When John Boyd developed the OODA loop, C2 models required minimal intervention from technology. Command centers now control battle spaces that span continents and deal with an ever-more complex threat that requires dynamic decision making under high degrees of uncertainty. It is often difficult for warfighters to develop and maintain sufficient situational awareness to make critical decisions without the aid of decision-support systems (DSSs) that help keep track of all the moving parts of the battle space.

Decision-support projects must provide decision makers in C2 with the tools and work environment that support rapid, accurate decision making, especially during times of high "operational tempo" where the "fog of war" prevails. Modeling and simulation tools provide the commander a more accurate understanding of the threat potential, the ability of the defensive systems to counter the threat, and the risk associated with executing one of many COAs. These tools have provided a more thoughtful *a priori* contemplation of the battle space before hostilities commence. The concept of the battle plan, a single plan of action that is normally overcome by events the moment the first shot is fired, has given way to a battle plan book with a plethora of options based on various enemy activities.

However, as positive as technology can be in helping the warfighter, dependence on technology can also paralyze the warfighter. Too many inputs, too much information, and too many options are just as debilitating as a lack of inputs, information, and options. Therefore C2 systems engineers must pay close attention to the needs of the commanders and their staffs when designing C2 systems. Failure to consider the operational environment will produce an elegant technological solution to the wrong warfighting problem.

Current C2 systems have evolved over the past decade, incorporating systems, automation, and tools that were developed on the basis of evolutionary processes in C2 planning and execution. As a result, these tools do not always directly support the decision maker. Instead, each supports specific portions of the process. Additionally, data and information presented to the decision makers by today's C2 systems are sometimes inconsistent, often presented in differing formats, and not always graphically displayed to support cognitive understanding and situational projection. Furthermore, the majority of the information presented is classified at multiple levels of security, resulting in a fragmented perception based on the information's classification level. As a result, warfighters often succumb to data overload and lack enough actionable information to effectively perform their functions and duties. The next generation of C2 systems must accommodate the entire decision-making cycle for each decision maker. Decision makers have different decision-making methods and time lines, and they need tools that are adaptive, not only to their differing decision-making methods, but also to their duty position.

THE CHALLENGE WITH C2 SYSTEMS ENGINEERING

Systems engineering and systems-of-systems engineering are described and dissected in great detail in many articles in this issue. This article examines the challenges in engineering a C2 system that by definition includes a random actor, namely a human commander, in the midst of the engineering process. In classical systems engineering, as applied to electrical and mechanical systems, a model of systems engineering can be extremely valuable to ensure that deliberate and complete engineering occurs. One such model is the systems engineering "V" model, shown in Fig. 3. Many successful systems have followed this model, where the systems engineer develops the concept of operations, refines the concept into system requirements, and then proceeds from high-level design to detailed design to software and hardware development. Once development is complete,

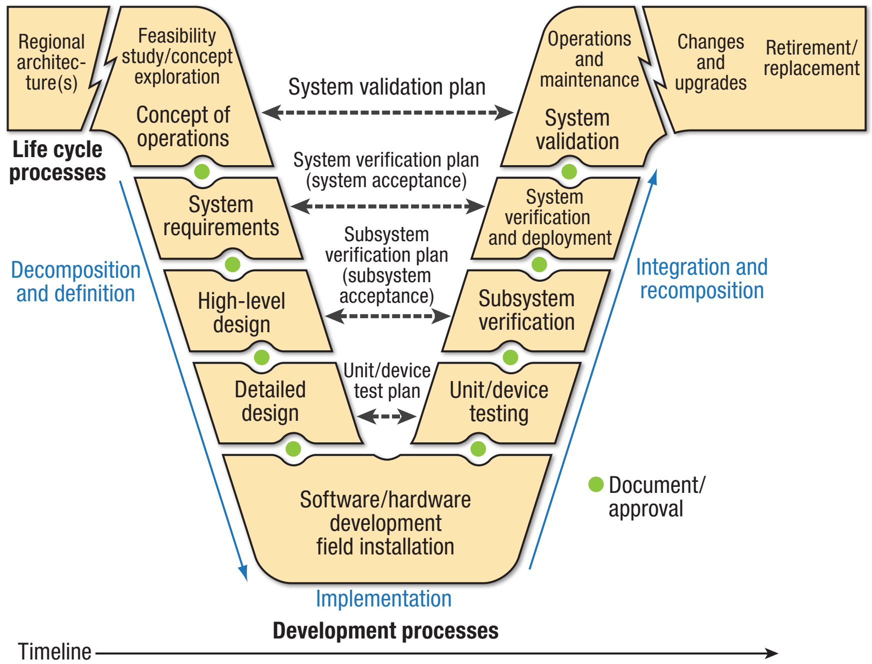

Figure 3. The systems engineering "V" model.

layers of systems-of-systems from the somewhat deterministic electromechanical capabilities of sensors and weapons, but also large teams of participants potentially spread across the globe. These command staffs may include hierarchical and bureaucratic responses to observed data, with many of the staff members handling data and adding their own analysis and expertise to the gathered data inputs. Each of these handlers of data in fact provides an additional nondeterministic variable to the performance calculations of a C2 system. This is particularly difficult because the humans are often the largest component of the performance budget.

These challenges have led a team from APL to undertake the development of a slightly modified systems engineering model that is more conducive to successfully guiding the engineering of C2 systems (Fig. 4). This model is cyclical in nature and supports each step of the cycle described in the Guest Editor's Introduction to this issue: the identification of critical challenges, the evaluation of the current systems to pinpoint the gaps in capability, the exploration of capabilities to close the identified gaps, the modeling of these capabilities to determine the likely effectiveness of the solution, and finally implementation and deployment of the solution. The benefit of this cyclical approach for C2 systems development is that, once deployment occurs, the systems engineering team needs to remain embedded with the command staff to determine whether the

the unit testing, subsystem verification, and system validation and verification are the logical steps necessary before deployment. Each of these testing and analysis steps provides opportunities for the systems engineer to ensure that both the functionality and the performance necessary for operation are met.

Unfortunately, on both sides of the V, there is the difficulty of determining the human element's effect on overall system performance. Unlike a sensor or weapons system, where system capabilities and performance criteria can be levied, system components can be developed, and the system can be tested to determine whether the requirements have been satisfied fully, partially, or not at all, C2 system performance is more nuanced and dependent on multiple systems, each involving at least one human. Human performance is complex and difficult to levy and specify. Ranges of performance expectations within a context of employment for specific human performance factors (e.g., workload, timeliness, accuracy, and so on) are what a C2 systems engineer has to levy on design and development of a C2 system.

Furthermore, note that C2 systems engineering involves not only many

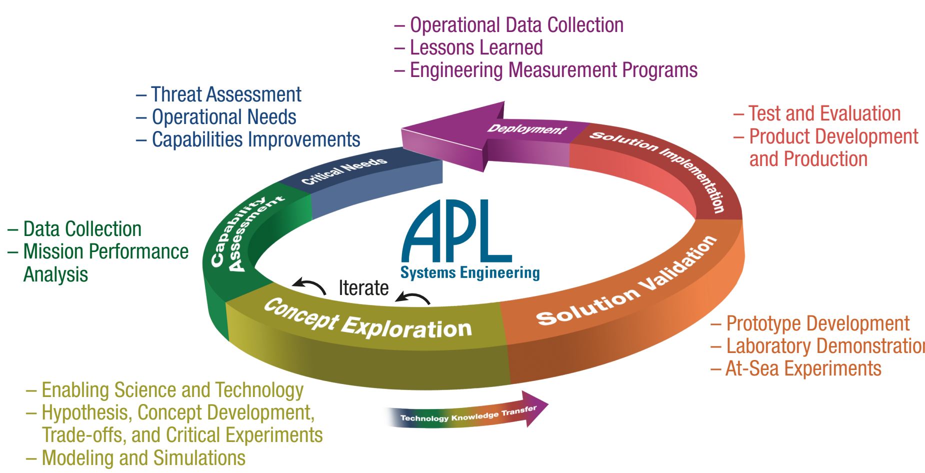

Figure 4. A cyclical model of systems engineering.

developed capability has indeed closed the previously identified gaps and if so, whether closure of those gaps uncovers further gaps in capability that reduce the effectiveness of the C2 process.

A deeper investigation of this model of systems engineering and its applicability to C2 systems reveals that this approach also supports incremental development of multiple systems that will necessarily be integrated into a holistic C2 system. This incremental approach is provided through the up-front needs definition and capability improvement activity. The need sets the stage for the objective C2 system, and the capability improvement plan defines how it will get there. Each component (system for the system) then undergoes the engineering cycle with a common foundation of requirements. This approach helps to ensure that when the parts are integrated, they result in the planned whole, as evidenced through a verification process. The addition of cognitive engineering/human-systems integration (HSI) also helps to ensure that these cycles of development meet the user needs and expectations supporting C2 warfighter decision making. This type of approach is represented in Fig. 5.

RAPID PROTOTYPING AND KNOWLEDGE ENGINEERING

The cyclical model of systems engineering includes spiral development, rapid prototyping, and knowledge engineering to develop and field C2 systems. The spiral development methodology lends itself well to the concept of rapid prototyping. As the engineering team peels back the layers of the critical needs, capabilities can be developed to close the most difficult challenges. As these capabilities come online, the critical need may shift, unintended warfighter performance challenges may emerge, or the engineering team may find another critical need that may have been obfuscated by earlier challenges. As the engineering team continues to develop and the prototype team builds and evaluates these capabilities with representative end users, the teams not only provide better systems for the warfighter's use, they also become more aware of the warfighter's challenges. The Battle Group Anti-Air Warfare (AAW) Coordination (BGAAWC) Program is an excellent example of this phenomenon. Over a period of a dozen years, these engineers worked on a series of systems designed to improve the AAW capabilities in the fleet. Each system undertaken was derived from the experiences gathered while under way. An excellent example was the genesis of the Dual Net Multi-Frequency Link Program. The BGAAWC team was working with ship's crew, supporting the Automatic Identification Program, and noticed that while the identification was improving, the improvement was stymied by reduced radio connectivity during certain weather phenomena. This identification of a critical challenge spawned the capability that became the Multi-Frequency Link Program, which in turn spawned the Dual Net Multi-Frequency Link Program, a program that not only significantly improved connectivity, but also allowed the proper connectivity for the Automatic Identification Program to maximize its effectiveness.

The task of rapid prototyping for C2 systems engineering often involves significant knowledge engineering. The knowledge engineering field was made popular by the artificial intelligence movement of the late 1980s. The concept of artificially intelligent "expert systems" included a methodology and scientific approach to gather system heuristics that expert humans employed. These heuristics would then be incorporated into a series of inductive and deductive logic statements that could be run exhaustively to find the "intelligent" solution. Most C2 systems do not attempt to replace humans and their associated knowledge. However, the use of these gathered heuristics does allow the C2 systems engineers to identify the differences between processes that can be more readily accomplished by the power of the computer and processes that require the intervention of a human to sort out the best answer. In this way, the developed C2 sys-

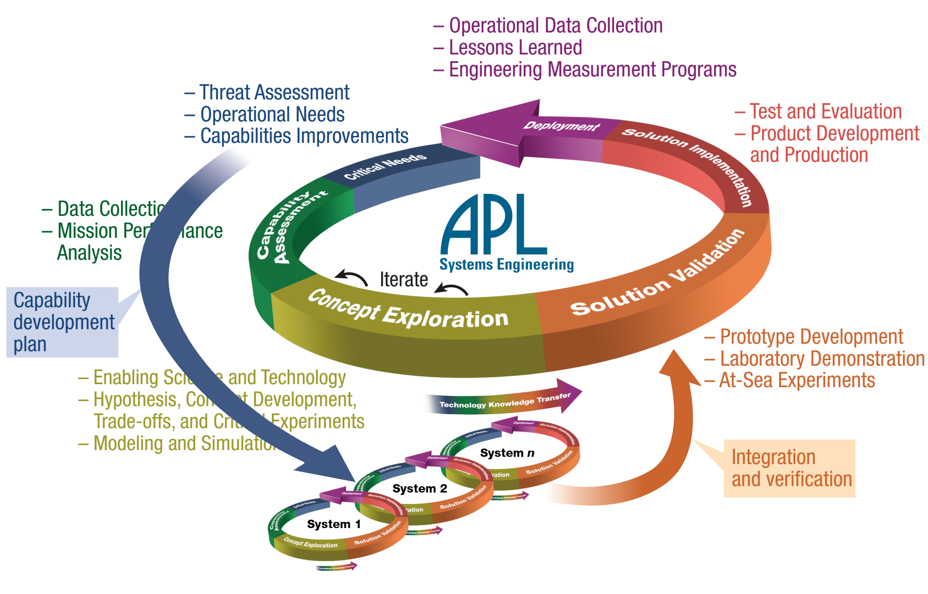

Figure 5. C2 system-of-systems engineering model.

tems can augment the human processing by providing the "heavy lifting" in terms of computation, thus allowing the commander to focus on the decisions.

An example of the separation of tasks between the commander and the automation can be seen in C2 tools such as weapons allocation processors. In such systems, the computer models the entire set of possible blue-on-red intercepts, determines which set of intercepts provides the highest probability of raid annihilation, considers the spatial and temporal requirements associated with the rules of engagement, and presents the options to the commander for final decision. In this manner the computer is doing the billions if not trillions of mathematical computations that humans cannot do in a timely manner. However, the automated tool does not make the decision; it only provides information to the commander. The human then contemplates considerations that cannot be readily quantified into computer logic to make the final decision. In extreme cases, the human may, after a long period of building trust in the system, decide to remove himself from the process, but this is normally done in a highly defined and constricted manner.

The challenge with knowledge engineering is finding the experts. Many of the C2 system challenges the community faces today are understood by very few commanders. The Force AAW Coordination Technology (FACT) Program, circa 1997–2002, provides an excellent example of this challenge. For years the program had been working on ship and battle group systems, but in the late 1990s the Navy asked the team to develop a theater capability. As the project attacked this latest challenge it soon became evident that ship and battle group knowledge and tactics could not necessarily be extrapolated to theater and combatant command tactics. Hence, the program manager sought out experts who could provide the knowledge necessary to build the Area Air Defense Commanders Command Support Capability. Three flag officers ultimately formed the expert team that advised the development team on this project. Without their expertise and their commitment to working with the engineering team for several years, the system would not have met the needs of the warfighter. Culling the flag officers' knowledge and experiences in various roles of theater command was crucial to developing a tool that would provide the information the commanders need to operate successfully.

There are challenges associated with the spiral development and rapid prototyping methodology. The most immediate of these challenges is gaining access to the environments that will enable the system developers to work closely with the warfighting customers. There is no substitute for actual at-sea experience. The best constructive simulations are just that, simulations. Although the Navy has spent considerable effort and dollars constructing hardware-in-the-loop simulation capabilities, these capabilities cannot replicate the anomalies that occur while under way. The simulations do provide an excellent environment for analysis, modeling, and early testing, but to truly gain the benefits of spiral development with rapid prototyping, the engineers must be embedded with the warfighting staffs. This is particularly true in the area of C2. Although small team simulators (i.e., aircraft simulators) have been developed to effectively test the C2 decision processes, it is very difficult to expand that encapsulated simulation environment to a globally distributed C2 environment. Furthermore, it is difficult with large groups of people to fully simulate the "fear factor" associated with the stressors and fog of warfare. Understanding these facts, the Navy regularly conducts full-scale at-sea exercises to provide the appropriate environment for training and evaluation. The use of the rapidly prototyped capabilities during these exercises is invaluable for the systems engineer. In fact, many systems have significant data-gathering and -reduction tools to capture data from these events because of the unmatched value associated with these exercises.

Unfortunately the results from rapid prototyping experiments are often disregarded by some in the engineering community. The term "anecdotal engineering" is used far too often to discount the fact that certain systems are being employed with great success. Rapid prototyping is not designed to conduct controlled experiments. It is designed to provide capabilities quickly and to morph those capabilities through spiral development by interacting with the warfighters in the operating environments. The results of these efforts can be quantified more qualitatively than quantitatively. Hence, some engineers would abandon this methodology and would instead choose experimentation to determine the best solution to a critical challenge. This is unfortunate, as the concept of rapid prototyping is used in almost every field of endeavor. (Think focus groups for television and advertising, beta releases for software, and car shows for the automobile industry.) None of these efforts truly measures anything more than anecdotal evidence of what is good, yet companies regularly use these methodologies to determine their future COAs. Furthermore, there are significant capabilities with reams of associated experimental data that have missed the mark completely. That is because these experiments worked extremely well in a controlled environment, which unfortunately was not the environment in which the warfighter happens to operate. As previously stated, creating a C2 environment with the appropriate depth, scope, and fear factor that approximate warfare is extremely rare.

COGNITIVE ANALYSIS AND DECISION ANALYSIS APPROACHES

Achieving the desired impact with new C2 systems requires an understanding of human information processing and of the decision making that is generated through cognitive analysis. This understanding needs to be fully integrated with the other systems engineering activities. Cognitive engineering products must be the result of a disciplined engineering effort that is conducive to overall system analysis. This integration will help to deliver robust decision-support tools, as opposed to tools that provide additional information that may or may not be useful. The need for the information must be thoroughly understood. The decision that is being supported, the timing of the decision, how long one has to make it, the boundaries of certainty, and the amount of collaboration required are just a few of the attributes of the decision that must be understood to develop DSSs that actually support and enhance decision making.

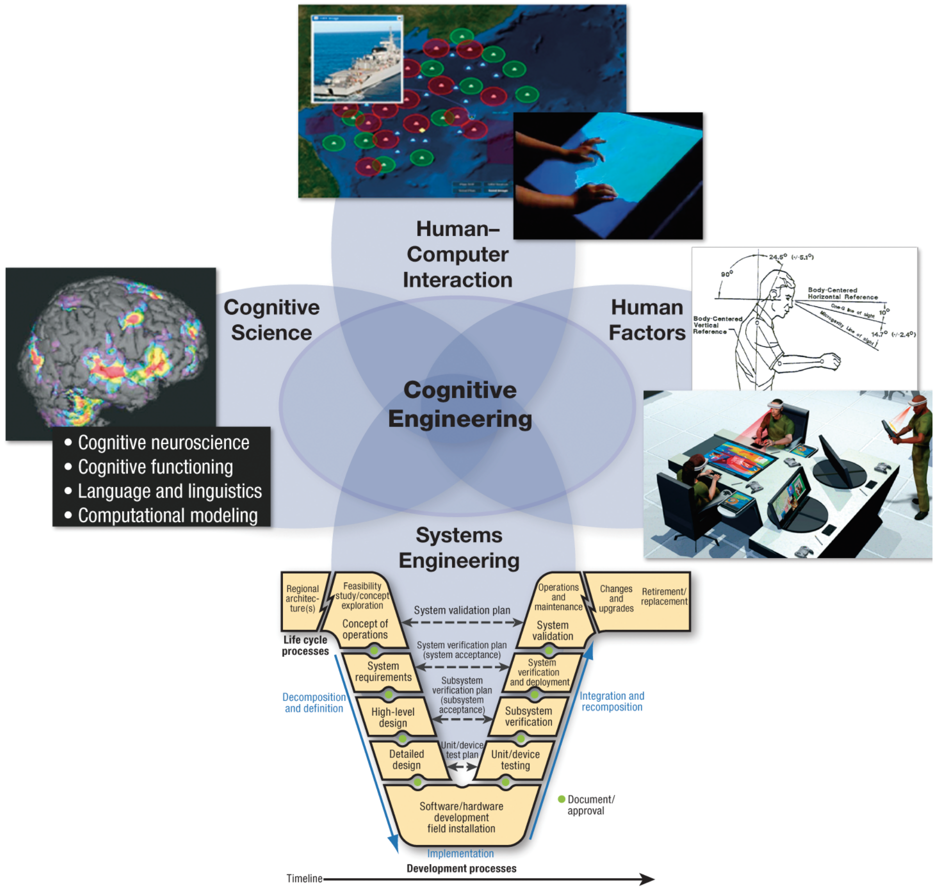

Figure 6. The influences on and impacts of cognitive engineering.

The analysis required to fully understand decision-making requirements is such that design innovation can be stymied or stalled too long while waiting for the result. Rapid prototyping allows early concepts to be mocked up and reviewed by warfighters early in the design process, allowing early, frequent, and less costly updates. As such, parallel and integrative methods of analysis and rapid prototyping need to be developed to enable technological advances to make it to the warfighter in a timely and useful way.

To understand the underlying issues related to information and decision making and to ensure that the design meets the needs of today's warfighters, the APL HSI team has developed an innovative decision-centered design process[4] that supports developing the decision-support requirements, identifying and articulating decision-support/situational awareness aids and automation opportunities, developing a prototype graphical user interface, and testing the graphical user interface to ensure that it meets operator requirements. This methodology for integrating the human element in C2 systems is founded on sound principles of cognitive engineering. After an introduction to cognitive engineering, the methodology is described in detail.

COGNITIVE ENGINEERING

Cognitive engineering is a multidisciplinary endeavor concerned with the analysis, design, and evaluation of complex systems of people and technology.[5] It brings together knowledge and experience from cognitive science, human factors, human–computer interaction design, and systems engineering (see Fig. 6). In C2 systems, cognitive engineering focuses on the cognitive requirements imposed by the operational context (i.e., operational tempo, organizational structure, connectivity) and on the sociotechnical factors where actions must be conditioned on the expected behavior of other C2 elements (human and autonomous).

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 so that overall system performance is enhanced. This goal is particularly important for C2 system design, with which warfighters use information from various sources to make critical decisions in the planning and execution of strategic and mission 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 mission success. An ecological perspective is a key common aspect of the different cognitive engineering approaches. The context in which the warfighter executes C2 is considered, forming an understanding of cognition "in the wild." The mental processes of the warfighter and the impact of environment on decision making are addressed: system objectives, people, artifacts, human goals, and the environment in which the goals are applicable are considered collectively and simultaneously. Cognitive task analysis (CTA) provides for the documentation and analysis of these considerations, where CTA captures people's tasks and goals within their operational context. Methods for systematically investigating the user's tasks, organizing the results of observations, and using this information to drive system design and evaluation have become foundations for HSI.

The methods of CTA, however, do not fully account for the complexity of C2. The recognition of this shortfall led to the development of the effects-based decision analysis methodology (EDAM), which employs the best practices from current cognitive engineering processes.

EDAM (see Fig. 7) begins with defining and documenting the context: scenario design and articulation and an initial work domain analysis. This context is then used throughout the process to support development of user profiles and to provide the foundation to consider design decisions that need to be made and demands of the environment and the system.

User profiles are critical products that provide the development team with the understanding of roles, responsibilities, information requirements, collaboration needs, and systems used. An example user profile is shown in Fig. 8 for the Undersea Warfare (USW) community.[6] User profiles can aid the developer in ensuring that different types of users' specific needs are supported. This information is particularly important in C2 environments, where many people need different types of information in different forms and at different speeds of response.

Knowledge elicitation follows the scenario development and should be conducted along two parallel paths addressing cognitive performance, one focusing on decisions and the other on the work environment. Knowledge elicitation methods include attending courses related to function; visiting training sites, command centers, and other C2-intensive sites; and interviewing subject-matter experts (SMEs) with semistructured and structured techniques. The collected knowledge of the cognitive processes and the environment in which these processes are performed is considered when the two paths converge, where representations of the knowledge elicited are produced. The analysis and the resulting representations lead directly to DSS design concepts. The Office of Naval Research-sponsored Exceptional Expertise for Submarine Command Team Decision Making (E2SCDM) Project applied this knowledge elicitation approach.[7] The team observed submarine command team training, interviewed more than 70 submarine operational command team officers and trainers, and reviewed submarine incident reports. This data collection and analysis supported insights into operational team practices and system design that are being researched to improve submarine command team performance.

The ability to meet the DSS design goals must also be considered. As a result of maturity, cost, and/or schedule constraints, the technology may not always support the realization of the concept. An assessment of technology maturity and feasibility is conducted and then combined with the DSS design concepts to create a total system design concept and, ultimately, a prototyped demonstrator. It is important to note that, although these steps are listed as a sequence, a great amount of concurrent and iterative work will take place between the steps; furthermore, there is a critical need for a multidisciplinary team that provides systems, human performance, software, hardware, and operational/domain views into the design effort. This iterative, incremental nature lends itself to the investigation of the software development rapid prototyping approach, and synergies between the two approaches (cognitive engineering and rapid prototyping) can be leveraged to support better design and analysis at a more affordable cost.

This combined rapid prototyping and cognitive engineering/human factors approach also lends itself to a key component of EDAM, which is human performance

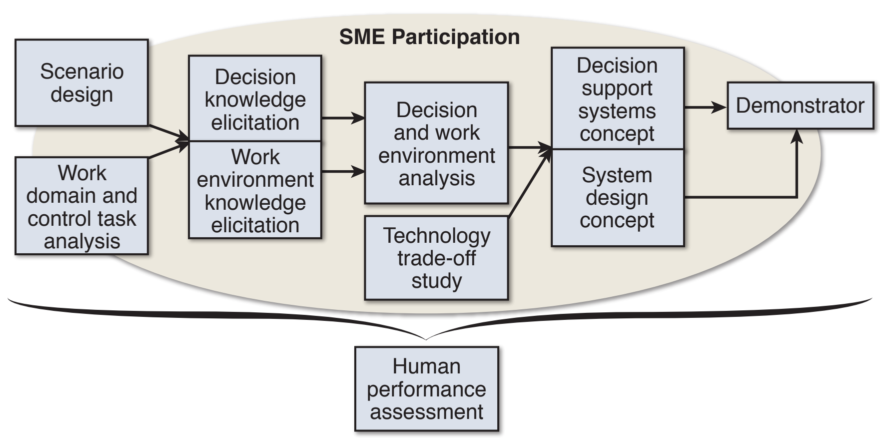

Figure 7. EDAM process diagram.

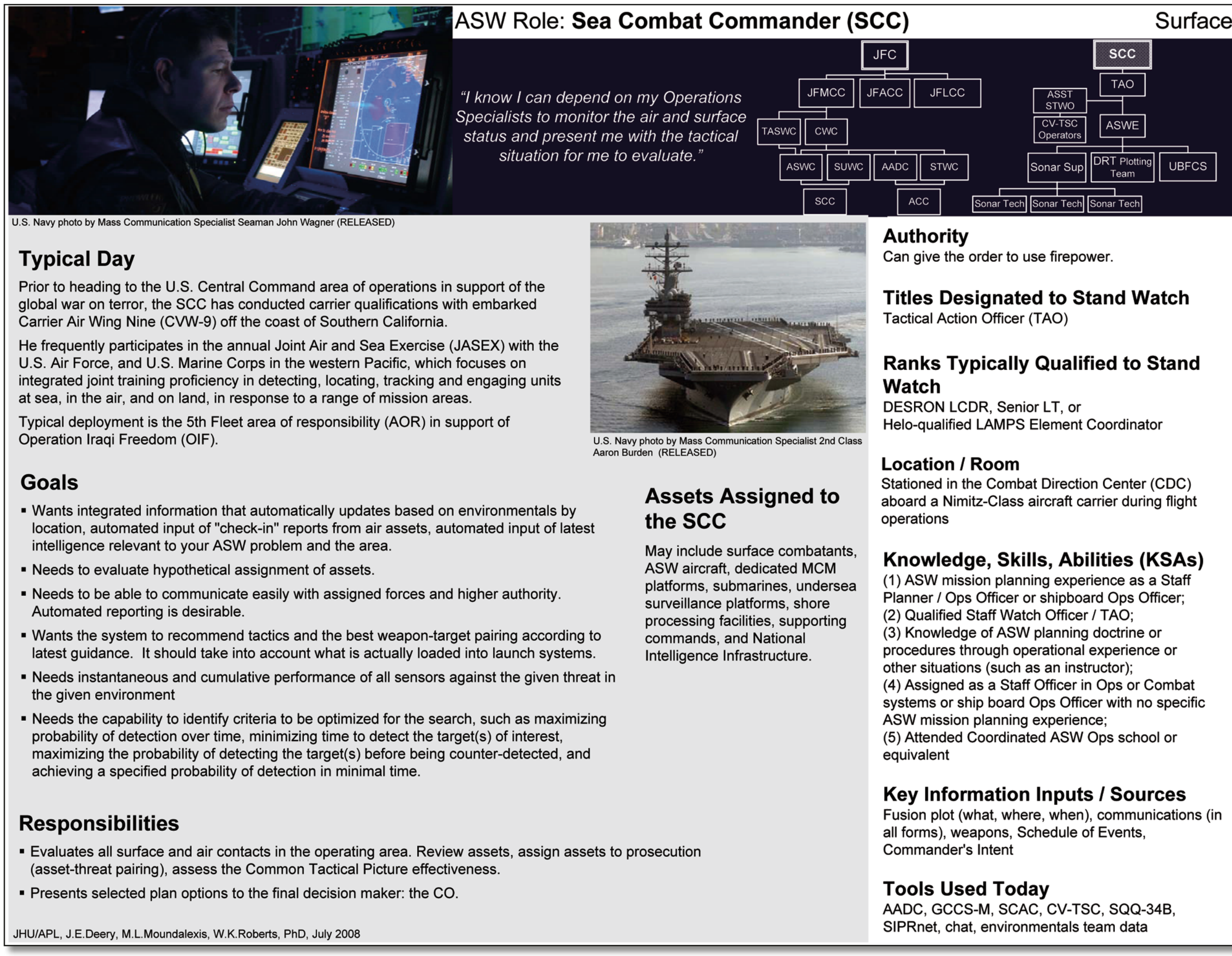

Figure 8. Example user profile.[6]

assessment, at all stages to the degree possible. Human performance assessment can be conducted at varying levels of prototype fidelity and maturity and can run from task walkthroughs up to full-scale, full-functionality human-in-the-loop measures of total system performance. A critical component to this testing is having the right metrics at the right level (Fig. 9). C2 systems span levels of performance; therefore, metrics must also span the levels of performance. Measuring human performance and diagnosing the impact on mission effectiveness is important; unfortunately, doing so remains difficult, particularly for decision making, because multiple measures, both objective and subjective in nature, are required.[8] Internal APL research has contributed to advancing metrics and maturing testing protocols; however, these metrics (i.e., for cognitive performance: neural correlates of human cognitive state, situational awareness, etc.) remain relatively immature and require more investigation.

Throughout the design and development process, participation of operational SMEs is absolutely 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 from both pools will participate in design evaluations.

Systems engineering aims to provide complete, detailed, and verifiable requirements as early as possible in the development process. Due to the complex interaction of humans and the context in which they operate, the cognitive/human factors team requires analysis of the candidate system architecture before they can fully develop valid requirements. To overcome the challenge faced by a C2 program (of incorporating early system-level human-performance-related requirements and detailing the design), we recommend that an incremental system development approach be taken, one in which requirements are identified, prototyped, evaluated, and further specified to mitigate system and operational risk. This approach was recommended by the National Research Council Committee on Human-System Design Support for Changing Technology.[9]

Key is documentation of analysis in such a way that systems engineering can incorporate the technical input. All too often input is not integrated into the design effort. To facilitate integration, cognitive engineering products

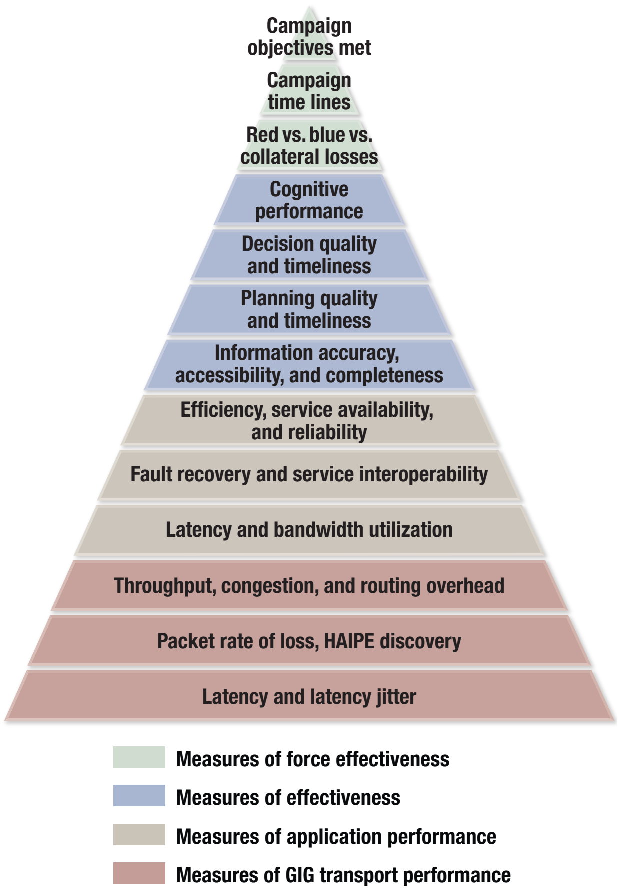

Figure 9. C2 metrics from effectiveness to system component performance. GIG, Global Information Grid; HAIPE, High-Assurance Internet Protocol Encryptor.

that are the result of applying the EDAM have been traced to the APL systems engineering loop (Fig. 10). In the early stages of system design, the user is identified and described and a needs analysis is conducted. This initial activity is based on the activities of scenario design and work domain and control task analysis. The products include user profiles, high-level requirements (needs), and a user-centered concept of operations.

THE JOINT COGNITIVE APPROACH WITH RAPID PROTOTYPING

When studying the methods used by the knowledge engineering and cognitive engineering communities, it is evident that there is much commonality between them. There is commonality with goals of the analysis and required inputs and information sources, as well as with the practical nature of the task (understanding knowledge and decision making with the aim of building DSSs/environments), as opposed to an academic aim. We believe that incorporating cognitive engineering analytical techniques with spiral development including rapid prototyping would meet the intent of the incremental system development approach and provide a tangible representation of the design sufficient to reduce risk and evolve the system solution. This integrated approach brings different perspectives and fundamental understandings together to tackle extremely challenging problems. The engineering team is now made up of individuals who have deep and rich understanding of software and hardware capabilities, those who have robust knowledge of human cognition and team performance characteristics, and those who have a firm grasp of the operational context and domain demands (as operational SMEs are key to any system design paradigm).

A rapid prototyping initiative provides the software development team with the ability to provide capabilities to warfighters and interact with warfighters in their environment to tailor the solutions to the critical needs at hand. While cognitive engineering may not provide the "macro" answer to how a global team will perform, it does provide valuable information describing how the user is interacting with the systems being developed. Knowledge concerning how the warfighter perceives information and whether the warfighter is being overloaded by either a plethora of options or an overabundance of information is critical in the design and fielding of a rapid prototype.

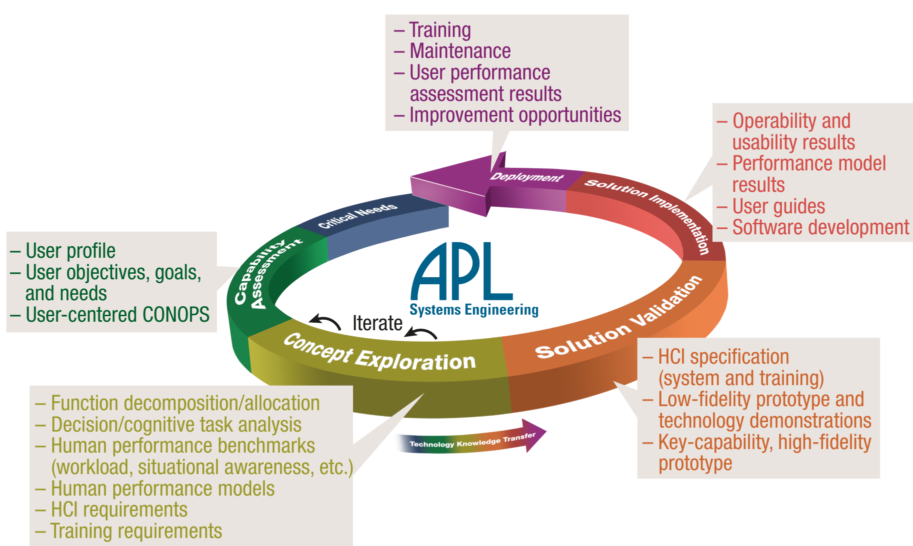

Figure 10. Cognitive engineering products within systems engineering. CONOPS, concept of operations; HCI, human–computer interaction.

With the advent of recent cognitive experimentation designed to map the physiological human response (even brainwave reaction) to information and recognition, the rapid prototypers are empowered with unprecedented insight into system design. This gathering of physiological data goes beyond the consciousness of the warfighter and defies the biases that tradition and status quo bring to more anecdotal evidence. Rapid prototyping also provides the cognitive engineering team with early opportunities to validate function allocation, task design, workload estimates, and operational concepts. The duality of benefits a rapid prototyping approach provides (both to the software developers and to the HSI teams) highlights the advantages of taking such an approach. Furthermore, the systems engineers can gain valuable system-level insights from human-in-the-loop rapid prototyping. Quantitative metrics can provide insights into the operational effectiveness of the concept, and qualitative metrics can give indications of user buy-in.

AN EXAMPLE OF A HYBRID APPROACH

The integrative method of build–test–build is inherent in the PEO IWS5 Advanced Processor Build (APB) Program. The APB Program is designed to bring continuous improvement and technology innovation into the submarine combat system. Historically, this program has implemented a thorough testing and analysis method combined with fleet feedback and operational effectiveness analysis to determine system improvement opportunities. Beginning in 2006 (and still continuing), the program officially integrated the human element of the system as a component to a total system evaluation methodology.[10] This analysis approach, called Watch Section Task Analysis (WSTA) (Fig. 11), calls for collecting comprehensive performance measurements of a submarine watch section that is using Acoustic Rapid COTS Insertion (A-RCI) and the BYG-1 Combat Control Systems using the Navy's shore-based Submarine Multi-Mission Team Trainer (SMMTT). The focus of WSTA is to analyze and understand the decision-making processes involved in executing a simulated mission scenario, to understand information flow between members of the watch section, and to identify the strengths and weaknesses of fleet-delivered sonar and combat systems in support of watch information flow.

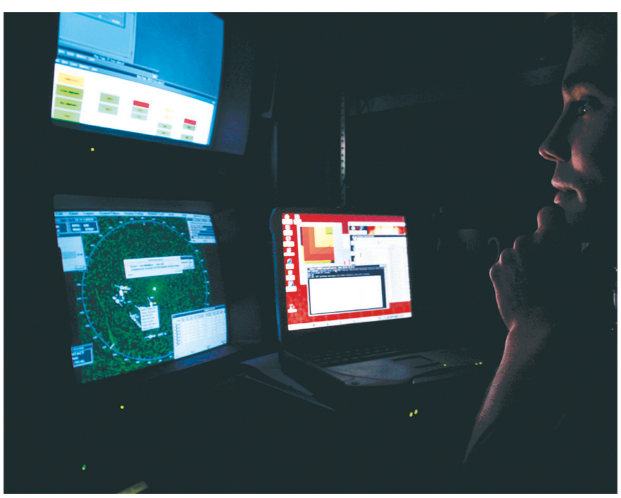

Figure 11. WSTA using SMMTT.[10] [Contact management displays on USS *Virginia* (SSN 774). Photo taken by Petty Officer 1st Class James Pinsky, U.S. Navy.]

Many of the WSTA process activities involved components of EDAM. The program is scenario based and involves SMEs throughout. Additionally, the in-depth understanding of the decision-making processes is a result of conducting task analysis, developing user profiles, and conducting and analyzing human–system performance testing in SMMTT by using stressing scenarios. This understanding resulted in a display concept that integrates real-time sonar waterfall data with active contact solutions to provide the commanding officer and the officer of the deck with a more intuitive, actionable tactical picture. System developers then transformed the concept to a working prototype, and the result is IBAL ("eyeball"), a 360° plan position indicator-type display specifically designed for the ship driver.

The integrated full system (hardware, software, and human performance) testing with fleet officers of the deck, commanding officers, and tactical teams from both Atlantic and Pacific fleets enabled the Development Squadron to target a 2008 installation of the IBAL capability, with employment guidance and training. WSTA introduces formal cognitive engineering approaches and products along with systems engineering as an embedded part of the planning, analysis, development, and testing of an APB. Coupled with engineering measurements, postevent analysis provides objective, statistically based feedback to the APB development and production system improvement process, system employment guidance, and submarine training.

The success of the PEO IWS5 APB Program has spawned similar initiatives in other Navy programs. The C2 Engineering Measurement Program (C2 EMP) for the USW-DSS was established to provide qualitative data to support a system design process fully coupled with real-world operational experience [Moundalexis, M., Ockerman, J., Croucher, A., and Dean, M., "Command and Control Engineering Measurement Program (C2EMP): Initial C2 Survey Findings from SHAREM 163," presentation given at the Joint Undersea Warfare Technology Spring Conference, San Diego, CA (8–11 March 2010)]. The focus of this evaluation was on USW-DSS capabilities and their impact on C2, as well as on the quality (timeliness and accuracy) of detect-to-engage execution. This USW-DSS Program has incorporated a warfighter-centered view and executed activities associated with the EDAM method. These include scenario development, user personas, and task analyses of selected functions.[6] These activities, coupled with the C2 EMP, will provide the program a rich systems engineering data set on which future capabilities can be developed and existing capabilities can be improved.

CONCLUSIONS

From the examples described in this article, it is clear that there is merit in combining the systems engineering practices of rapid prototyping and cognitive engineering. Although we may not be able to replicate the cognitive experimentation in the globally distributed C2 environment, we can utilize the practices of this discipline to gather unbiased results of how warfighters react to certain information stimuli and to understand more fully the decision processes that drive C2. Likewise, although rapid prototyping may not provide quantitative proof of improvement, it can be developed using the results of cognitive engineering to develop capabilities that can be tested by use in large, distributed applications to solve the critical C2 challenges the warfighter faces today.

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