Cognitive Engineering: Understanding Human Interaction with Complex Systems

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Cognitive engineering—a multidisciplinary field that focuses on improving the fit between humans and the systems they operate—emerged in the early 1980s and has many applications, including intelligence analysis and command and control. The APL Cognitive Engineering Program leverages the Laboratory's strengths in both cognitive engineering research and human-system integration. The challenge is to implement those strengths through changes in APL's culture, organization, engineering policy and practices, and a course of action toward implementing these changes.

THE NATURE OF COGNITIVE ENGINEERING

Cognitive engineering is a multidisciplinary endeavor concerned with the analysis, design, and evaluation of complex systems of people and technology.[1] It combines knowledge and experience from cognitive science, human factors, human-computer interaction design, and systems engineering. However, conitive engineering is distinguished from these applied research disciplines in two primary ways: its specific focus on the cognitive demands imposed by workplace environments and its concern with complex sociotechnical domains in which actions must be conditioned on the expected behavior of other agents, both human and autonomous (see the article by Watson and Scheidt, this issue).

Cognitive engineering (sometimes called cognitive systems engineering) was identified as an important activity in the early 1980s, though it has earlier roots in human factors and ergonomics.[2] It arose in response to transformations in the workplace spurred by two major sources. First, computer systems were escaping from the confines of machine rooms; design principles were needed to ensure that ordinary people would be able to use them.[3] Second, safety-critical systems were becoming more complex and increasingly computer-controlled; design principles were needed to ensure that teams of skilled technicians could operate them safely and efficiently.[4] The incident at the Three Mile Island nuclear power plant in 1979 demonstrated the latter and motivated subsequent research and investment. Analysis showed that team organization and the displays and controls in the plant control room did not support operators' rapid recognition of the state of the plant and the proper actions to take to achieve a safe condition. At the same time, analysis of commercial aircraft accidents could trace pilot error increasingly to faulty use of complicated automated flight deck systems. Even though the flight deck automation decreased accidents overall, a new pattern of accidents emerged.[5]

Subsequent work, growing out of earlier studies of cognition and the emergence of cognitive science, focused on how people actually interact with complex technical systems. During this same period, human-computer interaction became a recognized field within computer science, though it, too, grew out of earlier work going back to Vannevar Bush's seminal work, "As We May Think"[6] in 1945 and J. C. R. Licklider's work at ARPA[7] in the 1960s.

Like most intellectual domains, various approaches to and theories of cognitive engineering have been developed, and while differing in important ways, they all tend to involve a few key concepts: the design of complex interactive systems involves an ecological stance, and the design must simultaneously consider people, artifacts, human goals, and the environment in which the goals are to be achieved. That is, design must be based on the observation and understanding of system users "in the wild." In response, cognitive engineering has emphasized observation and understanding directed toward developing a cognitive task analysis that captures people's tasks and goals within their work domain. That is, cognitive task analysis represents people performing domain tasks using the concepts and tools of their domain such as documents, aircraft, solar coronal mass ejections, and other people. Methods for systematically investigating users' tasks, organizing the results of observations, and using this information to drive system design and evaluation have become foundations for the emerging engineering discipline of human-systems integration (HSI). The inherent systems approach of cognitive engineering means that the human user must be understood in the context of task, tools, and work environment. This has given impetus to the emerging field of cognitive modeling, which seeks to capture both the contribution of the domain and the computational characteristics of human cognition that constrain how we respond to our environment.[8]

In recent years, these approaches and methods have been applied to prevalent issues of information overload and sense making. The application of cognitive engineering approaches to areas such as intelligence analysis and command and control is receiving increasing attention.

CRITICAL COGNITIVE ENGINEERING CHALLENGES IN APL'S ENVIRONMENT

The lure of technology has been that it will make our lives easier. The reality is that technology has made our lives more stressful than ever. Our bosses have continuous access to us (Blackberries, cell phones, and DSL), our customers have fewer resources and are therefore demanding the highest performance at the lowest cost, our adversaries are striving for the competitive edge and have instantaneous access to the same information as we do, our families just want our time, and the information technology industry continues to give us ever more gadgets to help us balance these often competing demands. People are left to navigate through the morass of technology to cobble a "system" together that they can use to meet their performance requirements.

Information technology affords tremendous capacity for data transfer by increasing the availability of data, enabling interoperability between systems, and massively increasing bandwidth and processing. One result is people (warfighters, students, health-care professionals, educators, bankers, etc.) drowning in data and information while frequently lacking real knowledge.

Goal-based performance requires that information be transmitted seamlessly as knowledge to the decision maker. To achieve this, the human must be actively involved in information transformation by synthesizing his/her experience with available information to generate useful knowledge. We can no longer rely on information systems to push this information; it must be ubiquitously available on demand (available for pull). Total system performance includes the human element, which is now the limiting factor. It is incumbent upon system developers to be more understanding of this environment and of the human role within the overall system.

System complexity is moving the role of systems engineering away from a single individual being a forcing function of hardware and software decisions to that of an interdisciplinary team collaboratively integrating hardware, software, and human considerations in system design trade-off analyses and decisions. This enables the systems engineering process to be more robust and responsive to mission requirements (Fig. 1). If hardware, software, and human interaction requirements are not integrated during design, it will fall on the human user/operator/decision maker to do that integration in addition to the work demands of the job at hand. System design deficiencies become operations problems and require highly skilled users to overcome these deficiencies. These skill requirements drive increased training demands and potential user availability problems. The human systems engineering process has matured substantially to a point where it can be implemented hand-in-hand with traditional systems engineering activities to give the human an equal footing at the design table.

The goal of cognitive engineering is to provide a better fit between the human operator and the system so that the operator can more effectively perform tasks. This goal is particularly important for systems where people are acquiring information from various sources to make critical and complex decisions. We have started to look for user preferences in terms of system design look and feel, but we will not achieve desired

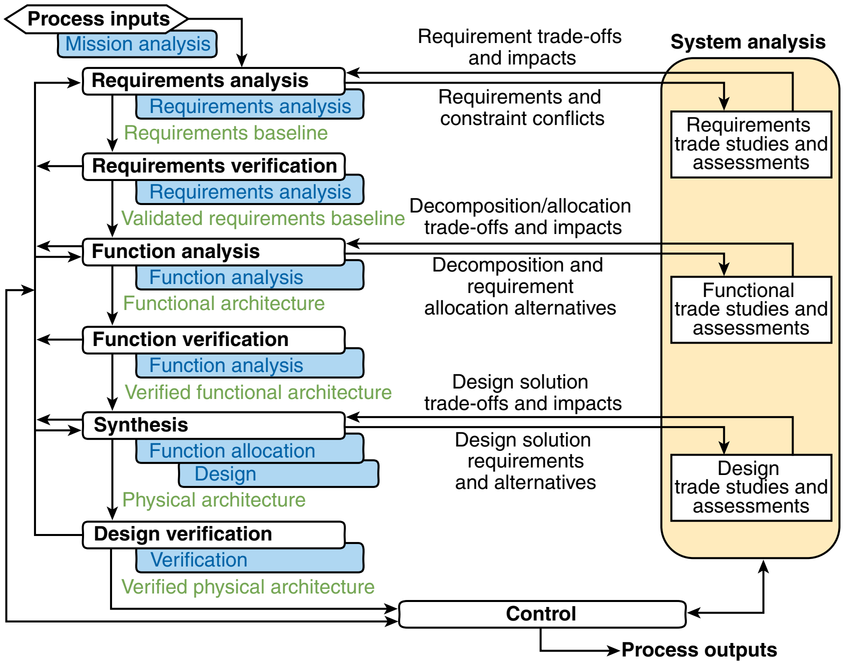

Figure 1. Systems engineering functions and activities.

performance gains until we also consider the human performance component.

The rapid and continuous advancement of technology makes the human more likely to be the limiting factor in system design and performance, making it increasingly important that the human factors and ergonomics communities work together with systems engineers.

ANALYSIS OF COMPLEX HUMAN-SYSTEM INTERACTION

How can one determine the impact of human limitations on system performance? How can one ascertain if task procedures, staffing, and human-system interfaces are designed to promote effective performance? These and similar questions about human performance in complex systems have been surprisingly difficult to answer. Yet such answers loom large as human-systems engineers struggle to design human roles and interfaces for ever-larger systems with increasingly sophisticated automation. All too often designers are left with the choice of assessing human-system performance in expensive full-mission simulations or by estimating human capabilities from handbooks and guidelines. Neither approach has proven satisfactory. Increasingly, DoD and NASA sponsors have been supporting the development of computer simulation to explore joint human-system performance. In such simulations human behavioral characteristics are represented in a computer model of the operator. Relevant domain knowledge, goals, and procedures are formally described and represented in a human behavior model that uses task theory processing to generate output in response to system states. A model of the dynamic system (for example, an aircraft) is used to generate the effects of the chosen behavior. Ideally, a computational simulation would allow one to explore the consequences of interesting or rare events or to estimate of the effect of a system change on the human decision maker.

Current human behavior models can make very accurate performance predictions for a single individual interacting with a simple state machine such as an ATM.[9] Recent research has shown promising results for predictions in more complex, dynamic domains such as air traffic control,[10] with extensions to team interactions.[11] APL is now establishing a capability for computational human behavior modeling and will pursue a fast-follower, early-adopter strategy with the goal of providing a human performance modeling capability that can be applied to more complex domains (particularly military and homeland security).

RESEARCH/PRACTICE CONNECTION

There is a move in research and development away from developing technology for its own sake and pipelining it into engineering solutions to one where the R&D is intertwined with the engineering and development practice. As depicted in Fig. 2,[12] the research loop from understanding basic human information processing to observing and analyzing technology developed in support of that understanding is intertwined with engineering and design primarily through the development of prototypes. These prototypes represent the researchers' design concepts and technology proposals to be used as seeds for the development of the operational functionality required by the systems engineers.

Having these prototypes for engineering design and development gives us a mechanism for learning more about human performance and information processing requirements in an operationally relevant context. This provides additional information to improve the design of the system under development and enables identification of human performance issues that require further research. This model creates a symbiotic relationship between research and engineering and design, where each supports the other in terms of identifying issues and enhancing the knowledge base.

APL is a gold mine of resources both to expand our knowledge of human information processing and

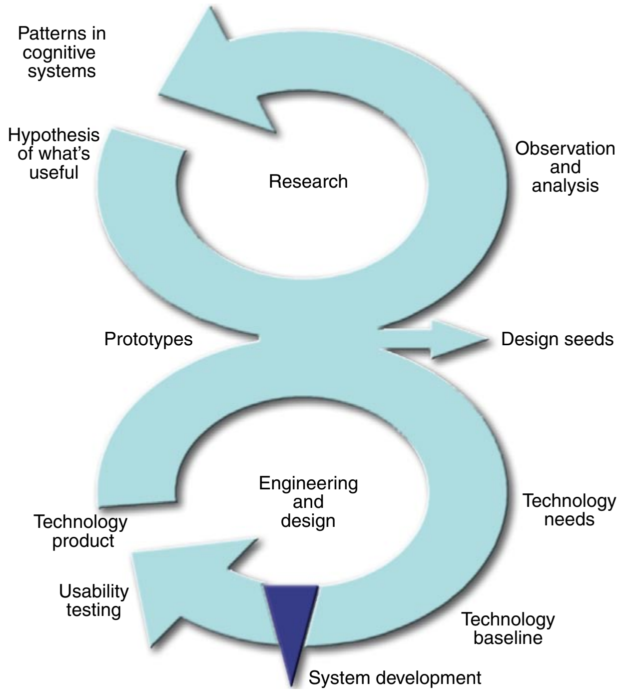

Figure 2. Another view of systems engineering functions and activities.

to improve system design based on that research. Our unique R&D environment lends itself to this new paradigm of R&D. We can leverage our engineering and design efforts to identify technology needs and seamlessly flow those needs into our research efforts to better understand human information processing R&D needs through the development of prototypes and evaluations of existing systems. This enables us to conduct science and technology studies of human performance in the context of systems and the environment in which work is performed. We have a large variety of prototype development efforts in addition to our support of sponsors in current acquisition programs. The result can be overall system performance increases (likely at reduced life-cycle costs) because of improved and better focused training, identification of the right person for the right job, and optimization of the human interaction design for people.

THE VISION

With the cognitive engineering R&D opportunities available at APL through our engineering and design efforts, our vision for cognitive engineering, as noted earlier, is to be a fast follower, early adopter. Our goal is to increase our activities in cognitive engineering in terms of research on human behavior in complex systems and the engineering and design of new systems, as depicted in Fig. 3. To ensure that the technology to meet future challenges is available when needed, we

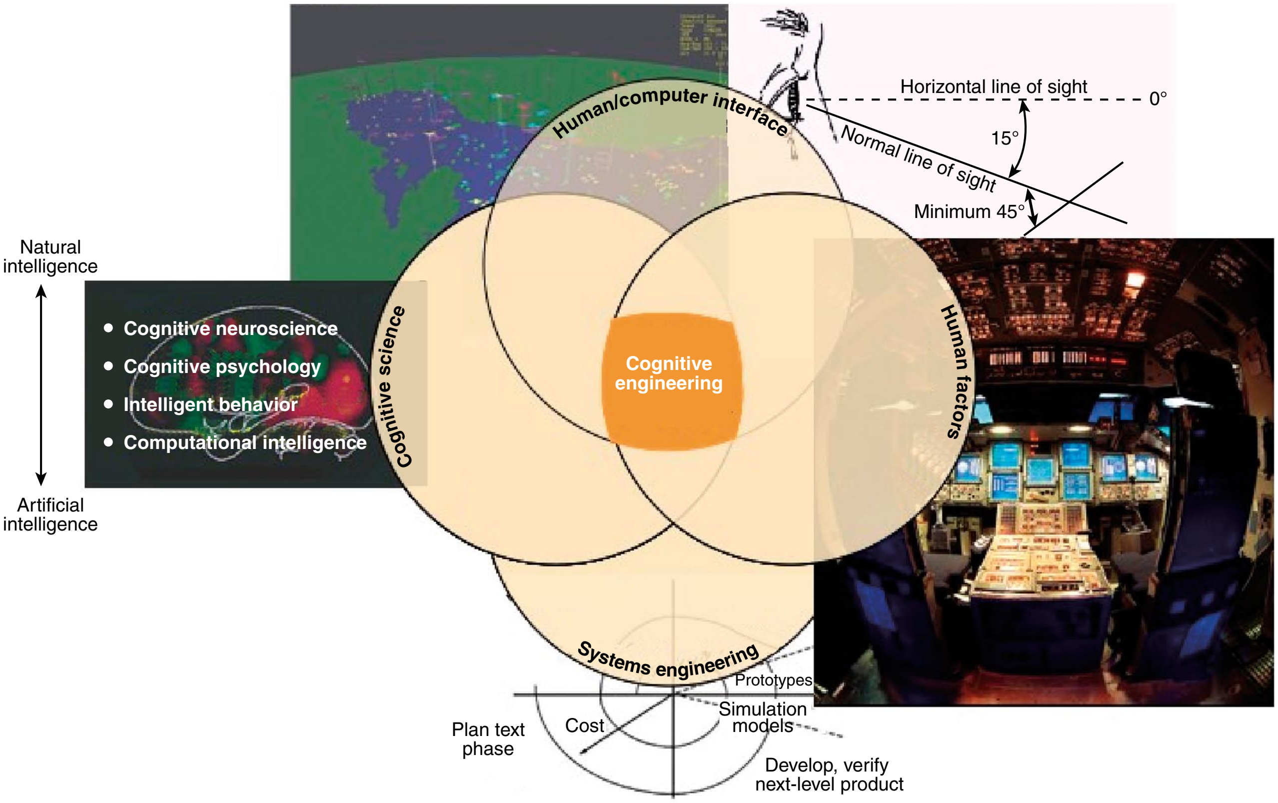

Figure 3. Cognitive/human performance science and engineering.

are establishing an active research program initially focusing on human supervision of autonomous systems and on dealing with information in massive collections, i.e., finding relevant information and making sense of it.

Autonomous systems are an advancing technology, but the technology is only now beginning to address the role of the human in directing and understanding autonomous action. Similarly, a concentrated effort is being applied to automated mechanisms for collecting and processing massive amounts of information, but concentrated concern for the analysts supervising this process and using its product is also just beginning. Addressing these challenges will enable APL to make significant technological contributions to needed capabilities in these areas. We also need to integrate cognitive engineering into engineering and design. Therefore, HSI principles and practices are being developed and incorporated into the APL systems engineering approach.

In addition to principles, the APL Cognitive Engineering Program will also develop task and cognitive user models to improve the tools available to human-systems engineers. Task models describe the jobs people do, the expertise required, the decisions that must be made, and the information needed to make those decisions. However, an understanding of the user is required to know how those tasks will be done, what errors are likely, what workload levels will be involved, and how to best support the user. These issues are currently dealt with largely by using the judgment of domain experts in conjunction with HSI teams. While expert judgment will continue to be the dominant source for design, computational models of the human user are proving increasingly capable of simulating the routine behavior of users that constitutes a large portion of task performance. Modeling and simulation could save time and effort in design by predicting workload and throughput for routine performance. Because of APL's strengths in both cognitive engineering research and HSI, the development of modeling and simulation in support of HSI, and its transition into design practice, will be a central focus of APL's cognitive engineering efforts.

IMPLEMENTATION

To address these challenges, APL has begun research and technology development projects in the focus areas just mentioned.

We are addressing needs for the effective and efficient human supervision of autonomous vehicles through a project to provide space mission operations staff with advanced systems for interacting with these increasingly autonomous spacecraft. In particular, we are tackling the problem of providing situational awareness of spacecraft and mission state to operations personnel who interact only intermittently with individual spacecraft. APL's recently launched New Horizons mission to Pluto involves extended periods in which the spacecraft communicates infrequently with the Earth, and then only to report its state of general health. Nevertheless, mission operations personnel will need to become quickly familiar with the state of the mission should detailed communications become necessary. We are applying cognitive engineering principles to develop a prototype space/ground control system that can address this general concern.

APL has also developed an interactive visual mechanism for intelligence analysts to explore information represented in complex social-network or communications-chaining graphs. We are now extending that approach to cover more general sense-making activities in partnership with an intelligence agency.[13]

To fully integrate HSI and cognitive engineering into the systems engineering practices at APL, an implementation pilot project was developed. This project embraces a grassroots campaign approach to make the APL engineering and program management community aware of HSI, the methods behind the principles, and the benefits of applying it within system development.

Successful implementation of cognitive engineering and HSI requires a number of changes. Implementing HSI with the aim of institutionalization requires not simply a change in engineering practice, but a cultural change as well. Our engineering work culture defines the way the work world is viewed, provides implicit instructions on how to respond to certain situations, creates notions of what is right and what is wrong, and tends to persist over time. The current APL engineering culture does not require that human considerations be made in system design. Some programs are starting to incorporate HSI, but they are few and their scope is sometimes limited. Changing the engineering culture requires leadership in HSI—a visible commitment from top management. This has been accomplished through the establishment of the Cognitive Engineering Steering Group and through department head and business area leadership support of the HSI implementation effort.

Institutionalization of HSI at APL also requires an awareness and education program to inform the workforce about HSI principles, how they are applied in system design and development, how to recognize HSI issues, and who to contact to support HSI. To accomplish this, two training programs have been developed, one for managers and one for technical staff, that provide the basics on HSI and explore how it fits within systems engineering and where it applies in systems acquisition. In addition to the training sessions, a website for those new to HSI provides high-level information and resources.

The HSI implementation project also includes the development of HSI technical guidance. State-of-the-art HSI practices and methods are being researched and leveraged. Guidelines will include information relative to the different stages of systems design, concept exploration, prototyping, and production, in addition to how HSI could be applied within each of those stages. It is recognized that all APL projects do not necessarily follow the same design path and that the HSI guidance must support the different branches within the path.

The HSI implementation project is also tracking specific programs/projects that are actively applying HSI principles. These include the Undersea Warfare Decision Support System, the SQQ89 Data Fusion Function Segment, and R&D projects focusing on situational awareness and fatigue as well as 3-D audio for enhanced detection of undersea targets. Metrics to assess HSI impact are also being developed and will be reported on.

These components to the project—training and education, engineering guidance, and HSI-related efforts—are all bounded by strategic planning. Understanding the state of the art in HSI and the HSI needs of existing APL projects translates into R&D opportunities for the future.

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