# A ROADMAP FOR COGNITIVE ENGINEERING IN SYSTEMS ENGINEERING

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We are concerned with three challenges in the design of military Command and Control (C2) systems, namely: the demand for "smaller" organizations, the demand for "better" coordination (human-system, human-human and system-system) and the demand for "faster" execution. Driven by these demands, we performed a survey of Cognitive Engineering techniques with an eye towards how they can improve Systems Engineering efforts. This paper outlines our three challenges (smaller, better, faster) and reviews three successful applications by other Cognitive/Systems engineers faced with similar challenges. The applications employ Computational Cognitive Modeling (to address a demand for smaller), Cognitive Work Analysis (to address a demand for better) and Goal-Directed Task Analysis (to address a demand for faster). These three successes provide a practical roadmap for using Cognitive Engineering methods to address Systems Engineering problems in C2 as well as other domains.

## INTRODUCTION

In our view from MITRE's Center for Air Force Command and Control Systems, there are three fundamental challenges driving the design of current and future Command and Control (C2) systems. Simply stated, these challenges are: (1) "smaller" organizations, (2) "better" coordination (human-system, human-human and system-system), and (3) "faster" execution. For all three challenges, success clearly requires a blend of Systems Engineering, which focuses on machines (computers), and Cognitive Engineering, which focuses on humans (operators). Nevertheless, we have found that the link between these two engineering disciplines is not always obvious. Therefore, we have initiated efforts to make a more explicit connection between the methods of Cognitive Engineering and the problems of Systems Engineering.

Our initial effort was a comprehensive survey (Bonaceto, 2003; Bonaceto, 2004; Bonaceto & Burns, 2003) of Cognitive Engineering methods and Systems Engineering problems. The purpose of the survey was to: (1) identify general classes and specific examples of Cognitive Engineering methods, (2) identify general classes and specific examples of Systems Engineering problems, and (3) correlate the methods to the problems in a way that explicitly illustrates which methods of Cognitive Engineering are suited to which problems in Systems Engineering. The product is a "Methods Matrix" that summarizes over one hundred specific methods of Cognitive Engineering (in rows) and relates them to dozens of specific problems in Systems Engineering (in columns), highlighting those cells where a specific method of Cognitive Engineering (row) is suited to a specific problem in Systems Engineering (column). Figure 1 below is a simplified version of the Methods Matrix, which shows all of the same methods of Cognitive Engineering (rows) but boils the problems of Systems Engineering (columns) down to three: smaller, better, faster.

This paper presents an even simpler survey in bird's eye view. Here the survey takes the form of a few "success stories" that highlight fertile regions of the method/problem matrix. We present three success stories, one for each of the three C2 challenges: smaller, better, faster.

# Applications of Methods: Black Denotes Higher Opportunities

| Category | No. | Method | Smaller | Faster | Better |
|---|---|---|---|---|---|
| Cognitive Task Analysis | I.A.1 | Applied Cognitive Task Analysis (ACTA) | Black | Black | Black |
| Cognitive Task Analysis | I.A.2 | Critical Decision Method (CDM) | Gray | Gray | Gray |
| Cognitive Task Analysis | I.A.3 | PARI Method | Black | | |
| Cognitive Task Analysis | | | Black | | |
| Cognitive Task Analysis | I.A.4 | Skill-Based CTA Framework | Black | Black | Gray |
| Cognitive Task Analysis | I.A.5 | Decompose, Network, and Asses (DNA) Method | Black | | |
| Cognitive Task Analysis | I.A.6 | Task-Knowledge Structures (TKS) | Gray | | Gray |
| Cognitive Task Analysis | I.A.7 | Goal-Directed Task Analysis (GDTA) | Black | Gray | Black |
| Cognitive Task Analysis | I.A.8 | Cognitive Function Model (CFM) | | | Black |
| Cognitive Task Analysis | I.A.9 | Cognitively Oriented Task Analysis (COTA) | Black | | |
| Cognitive Task Analysis | I.A.10 | Hierarchical Task Analysis (HTA) | Gray | Gray | Gray |
| Cognitive Task Analysis | I.A.11 | Interacting Cognitive Subsystems (ICS) | Gray | Gray | Gray |
| Cognitive Task Analysis | I.A.13 | Team CTA Techniques | Black | Black | Gray |
| Interviewing / Observing Methods | I.B.1 | Unstructured Interviews | Gray | Gray | |
| Interviewing / Observing Methods | I.B.2 | Structured Interviews | Gray | Gray | |
| Interviewing / Observing Methods | I.B.3 | Step Listing | Gray | Gray | |
| Interviewing / Observing Methods | I.B.4 | Group Interview | Gray | Gray | |
| Interviewing / Observing Methods | I.B.5 | Questionnaires | Gray | Gray | |
| Interviewing / Observing Methods | I.B.6 | Teachback | Gray | Gray | |
| Interviewing / Observing Methods | I.B.7 | Field Observations/Ethnographic Methods | Black | Black | Gray |
| Interviewing / Observing Methods | I.B.8 | Twenty Questions | Gray | Gray | |
| Process Tracing Methods | I.B.9 | Discourse/Conversation/Interaction Analysis | Black | Black | |
| Process Tracing Methods | I.B.10 | Activity Sampling | Gray | Black | |
| Process Tracing Methods | I.B.11 | Think-Aloud Problem-Solving/Protocol Analysis | | Black | Gray |
| Process Tracing Methods | I.B.12 | Retrospective/Aided Recall | | Black | Gray |
| Process Tracing Methods | I.B.13 | Interruption Analysis | | Gray | |
| Process Tracing Methods | I.B.14 | Shadowing Another | | Black | Gray |
| Process Tracing Methods | I.B.15 | Shadowing Self | | Black | Gray |
| Process Tracing Methods | I.B.16 | Simulators/Mockups | | Black | |
| Process Tracing Methods | I.B.17 | Exploratory Sequential Data Analysis (ESDA) | | Black | |
| Process Tracing Methods | I.B.18 | Minimal Scenario Technique | | | |
| Process Tracing Methods | I.B.19 | Critical Incident Technique (CIT) | Gray | Gray | |
| Process Tracing Methods | I.B.20 | Cloze Technique | Gray | Gray | |
| Process Tracing Methods | I.B.21 | Critiquing | | Gray | |
| Process Tracing Methods | I.B.22 | Crystal Ball/Stumbling Block Technique | | Gray | |
| Process Tracing Methods | I.B.23 | Table-Top Analysis | Gray | Gray | |
| Process Tracing Methods | I.B.24 | Wizard of Oz Technique | | | Gray |
| Conceptual Methods | I.B.25 | Decision Analysis | Gray | Black | |
| Conceptual Methods | I.B.26 | Rating and Sorting Tasks | | Gray | |
| Conceptual Methods | I.B.27 | Magnitude Estimation | | | |
| Conceptual Methods | I.B.28 | Repertory Grid Technique | | Gray | |
| Conceptual Methods | I.B.29 | P Sort | | | |
| Conceptual Methods | I.B.30 | Q Sort | | | |
| Conceptual Methods | I.B.31 | Hierarchical Sort | | | |
| Conceptual Methods | I.B.32 | Cluster Analysis | | | |
| Conceptual Methods | I.B.33 | Multidimensional Scaling (MDS) | | | |
| Conceptual Methods | I.B.34 | Likert Scale Elicitation | | Gray | |
| Conceptual Methods | I.B.35 | Structural Analysis Technique | | | |
| Conceptual Methods | I.B.36 | Conceptual Graph Construction | Gray | Black | |
| Conceptual Methods | I.B.37 | Diagramming | | Black | |
| Conceptual Methods | I.B.38 | Laddering | | | |
| Conceptual Methods | I.B.39 | Influence Diagram Construction | | | |
| Computational Cognitive Modeling | I.C.1 | Keystroke Level Model (KLM) | | Black | Gray |
| Computational Cognitive Modeling | I.C.2 | CMN-GOMS (Card Moran Newell GOMS) | | Black | Gray |
| Computational Cognitive Modeling | I.C.3 | NGOMSL (Natural GOMS Language) | | Black | Gray |
| Computational Cognitive Modeling | I.C.4 | CPM-GOMS (Critical Path Method GOMS) | | Black | Gray |
| Computational Cognitive Modeling | I.C.5 | CAT (Cognitive Analysis Tool) | | Black | Gray |
| Computational Cognitive Modeling | I.C.6 | COGNET | Black | Black | Black |
| Computational Cognitive Modeling | I.C.7 | COGENT | Gray | Black | Gray |
| Computational Cognitive Modeling | I.C.8 | ACT-R (Atomic Component of Thought - Rational) | Gray | Black | Gray |
| Computational Cognitive Modeling | I.C.9 | Soar | Gray | Black | Gray |
| Computational Cognitive Modeling | I.C.10 | EPIC (Executive-Process Interactive Control) | Gray | Black | Gray |
| Computational Cognitive Modeling | I.C.11 | Apex | Black | Black | Black |
| Computational Cognitive Modeling | I.C.12 | MIDAS (Man Machine Integrated Design and Analysis | Black | Black | Gray |
| Computational Cognitive Modeling | I.C.13 | SAMPLE (Situation Awareness Model for Pilot-in-the- | Black | Black | Gray |
| Computational Cognitive Modeling | I.C.14 | OMAR (Operator Model ARchitecture) | Black | Black | Black |
| Task Analysis | II.A.1 | Behavioral Task Analysis | Gray | Black | |
| Task Analysis | II.A.2 | Operational Sequence Diagrams | Gray | Black | |
| Task Analysis | II.A.3 | Timeline Analysis | Gray | Black | |
| Task Analysis | II.A.4 | Operator Function Model (OFM) | | | Gray |
| Task Analysis | II.A.5 | Link Analysis | Gray | Black | |
| Computational Task Simulation | II.B.1 | IMPRINT (Improved Performance Research | Black | Black | Gray |
| Computational Task Simulation | II.B.2 | CART (Combat Automation Requirements Testbed) | Black | Black | Black |
| Computational Task Simulation | II.B.3 | Micro Saint (System Analysis of Integrated Network of | Gray | Gray | Gray |
| Computational Task Simulation | II.B.4 | WinCrew | Black | Black | Black |
| Computational Task Simulation | II.B.5 | IPME (Integrated Performance Modeling Environment) | Black | Black | Black |
| System Evaluation Methods | III.A.1 | Heuristic Evaluation | | | |
| System Evaluation Methods | III.A.2 | Walk-throughs/Cognitive Walk-throughs/Talk-throughs | | Black | Gray |
| System Evaluation Methods | III.A.3 | Formal Usability Studies | | Black | |
| System Evaluation Methods | III.A.4 | Rapid Prototyping | | Black | Gray |
| System Evaluation Methods | III.A.5 | Storyboarding | | | Gray |
| System Evaluation Methods | III.A.6 | Interface Evaluation Surveys | | Gray | |
| System Evaluation Methods | III.A.7 | Ergonomics Checklists | | | Gray |
| Descriptive Approaches | III.B.1 | Activity Theory | Gray | Gray | Gray |
| Descriptive Approaches | III.B.2 | Situated Cognition | Gray | Gray | Black |
| Descriptive Approaches | III.B.3 | Distributed Cognition | Gray | Gray | Black |
| Descriptive Approaches | III.B.4 | Contextual Inquiry | Gray | Gray | Gray |
| Human Reliability Analysis | IV.1 | Event Tree Analysis | | | |
| Human Reliability Analysis | IV.2 | Fault Tree Analysis | | | |
| Human Reliability Analysis | IV.3 | Failure Modes and Effects Analysis | | | |
| Human Reliability Analysis | IV.4 | Barrier Analysis | | | |
| Human Reliability Analysis | IV.5 | Hazard and Operability Analysis (HAZOP) | | | |
| Human Reliability Analysis | IV.6 | Management Oversight Risk Tree (MORT) | | | |
| Human Reliability Analysis | IV.7 | Work Safety Analysis | | | |
| Human Reliability Analysis | IV.8 | Confusion Matrices | | | |
| Human Reliability Analysis | IV.9 | Operator Action Event Tree | | | |
| Human Reliability Analysis | IV.10 | Generic Error Modeling System (GEMS) | | | |
| Human Reliability Analysis | IV.11 | Cognitive Reliability and Error Analysis Method | | | |
| Cognitively-Oriented Methods | V.A.1 | Cognitive Work Analysis (CWA) | Black | Black | Black |
| Cognitively-Oriented Methods | V.A.2 | Applied Cognitive Work Analysis (ACWA) | Black | Black | Black |
| Cognitively-Oriented Methods | V.A.3 | Cognitive Function Analysis (CFA) | Gray | Black | Black |
| Cognitively-Oriented Methods | V.A.4 | COADE Framework (COgnitive Analysis Design and | Gray | Black | Black |
| Cognitively-Oriented Methods | V.A.5 | Perceptual Control Theory (PCT) Approach | Gray | Black | Black |
| System-Oriented Methods | V.B.1 | Information Flow Analysis | | Black | |
| System-Oriented Methods | V.B.2 | Functional Flow Analysis | | Black | Gray |
| System-Oriented Methods | V.B.3 | Function Allocation | | Gray | Black |
| System-Oriented Methods | V.B.4 | Mission and Scenario Analysis | | | |
| System-Oriented Methods | V.B.5 | Signal Flow Graph Analysis | | | |

Figure 1. A “Methods Matrix” shows the applicability of Cognitive Engineering methods (rows) to Systems Engineering challenges (columns). Black boxes denote high applicability of a method (row) to a challenge (column), gray boxes denote medium applicability and white boxes denote low or no applicability.

## C2 CHALLENGE: "SMALLER" ORGANIZATIONS

Cutbacks in defense spending have forced the Armed Services to do more with less (Office of Naval Research). The challenge is to design new systems and re-engineer existing systems in order to obtain/maintain optimal performance with fewer people.

Studies of successful manpower reduction efforts in both civilian and military domains (Militello et al., 1998) show that one key is to identify "leverage points", i.e., critical aspects of a system/mission where small improvements in design and/or training can have high payoffs. A variety of Cognitive Engineering methods can be used to identify leverage points, including the broad class referred to as Cognitive Task Analysis (Schraagen et al., 2000). Also, the methods of Computational Cognitive Modeling are useful for making more quantitative predictions about how staffing levels will affect workload and performance in various scenarios. Such modeling is especially useful for evaluating proposed system designs or proposed training programs where there is not yet a system or program that can be tested with real people.

### Success Story: Computational Cognitive Modeling to Reduce Staff Level

Computational Cognitive Modeling is used to perform computer simulations of human behavior in the context of a system design. The models can predict the nature and number of errors that people are likely to make at various levels of expertise while using a particular system to accomplish a particular function.

In one successful application, Computational Cognitive Modeling (Ryder et al., 1998) was used to design a telephone operator workstation where the jobs of multiple telephone operators were combined into a single role. Since each individual job was previously performed using a different workstation, the problem was to design a new workstation that supported all of the jobs – while maximizing call-processing efficiency and minimizing retraining of existing operators. The COGNET framework was used to model operator expertise underlying each of the separate tasks, and (combining these tasks) to model the expertise needed by the "integrated" services operator. The model/results were then used to design a user interface that effectively supported the role of a single operator in performing all of the required tasks.

## C2 CHALLENGE: "BETTER" COORDINATION

In many domains, advances in automation have changed the role of human operators from manual control to one of supervisory control. However, systems do not think and talk like people, and this can leave human operators (as supervisors) wondering what the system is doing and why (Ranson & Woods, 1996)**.** Then, if/when the automation fails, human supervisors can have trouble recognizing and intervening. The challenge is to design automation that results in effective human-system interaction.

Studies of success and failure in coordination (Christoffersen & Woods, in press) show that one key is to make the activities of an automated system readily "observable" to human operators. In this regard, methods like Goal-Directed Task Analysis (Endsley et al., 2003) and Cognitive Work Analysis (Vicente, 1999) can help identify information requirements (i.e., what exactly should be made observable?) for human operators to achieve accurate "situation awareness".

### Success Story: Cognitive Work Analysis to Improve a Display

In one successful application, the methods of Cognitive Work Analysis (Bisantz et al., 2003) were applied in the early stages of designing a next generation US Navy Surface combatant. The objective of the analysis, which focused on a subset of personnel known as "watchstanders", was to allocate functions between humans (watchstanders) and systems (automation) – and to identify information that the automated systems should display to the human watchstanders.

The analysis constructed an “Abstraction Hierarchy” to represent the structure and purpose of the domain. At the top of the Abstraction Hierarchy are the highest level goals of ship (e.g., maintain survivability), followed by constraints that govern these goals (e.g., rules of engagement), followed by various functions (e.g., targeting) and finally ending with the physical systems (e.g., weapons) that implement specific functions.

The analysis also modeled various control tasks of undersea warfare using a “Decision Ladder”. A control task (e.g., submarine detection and classification) is a process that transforms a set of inputs (e.g., sensor returns) into a set of outputs (e.g., identified submarine). The Decision Ladder represents various stages of a process and resultant states of knowledge, independent of the entity that will actually carry them out (human operator or system automation or some combination thereof).

Finally, the analysis produced a series of “Matrix Mappings” that linked cognitive functions to information displays. These Matrix Mappings generated specific recommendations about the explicit (observable) information that watchstanders should have in supervisory control of automated systems, so that the human supervisors could effectively understand (and thereby supervise) the automated systems.

## C2 CHALLENGE: “FASTER” EXECUTION

In military missions, minutes or even seconds can make the difference between success and failure. The challenge is to design systems that allow good decisions to be made in less time. While there are obvious overlaps between “smaller/better” (see above) and “faster”, the focus here is on those aspects of a mission that are especially important to reducing a timeline.

The identification of leverage points can clearly help make C2 operations faster, by identifying where there are gridlocks in information flow (Militello et al., 1998). Here, “iteration” is important in making C2 operations both faster and better. This is because changes that are made to reduce the timeline may eliminate seemingly unimportant functions that actually serve a useful purpose (e.g., redundancy, to reduce errors). Typically, the unintended consequences are discovered only via “trial and error” (iteration), which is better to perform on the drawing board or in the laboratory than on the battlefield. For this purpose, the methods of Computational Cognitive Modeling can help predict the impact of new system designs on both the timeline and the quality of decision-making.

Training is also a key to a timeline reduction, especially when work is distributed among members of a team (Blickensderfer et al., 2000). In this regard, the methods of Goal-Directed Task Analysis (Endsley et al., 2003) and Cognitive Task Analysis (Schraagen et al., 2000) can help by identifying information that must be formalized and transmitted for the team to achieve a shared situation awareness.

### Success Story: Goal-Directed Task Analysis to Reduce a Timeline

In one successful application, a Goal-Directed Task Analysis (Endsley et al., 2003) was used to help design a prototype interface for Maintenance Control Center (MCC) specialists in the domain of air traffic control. MCCs are facilities that support technicians who service a national network of systems (e.g., beacons and communications equipment), allowing the technicians to monitor the states of various systems remotely for faster discovery and diagnosis of faults (i.e., reducing the timeline).

The objective of the analysis was to evaluate how well the existing MCCs support the “situation awareness” requirements of MCC specialists and to recommend a possible re-design. The analysis used Goal-Directed Task Analysis to develop a list of goals and tasks relevant to the MCC specialist’s job. The results were then used to evaluate the existing system and this uncovered several problems. For example, one problem was that MCC specialists had to page through several different screen displays/windows to find the information needed for a single goal. Another problem was that much of the information needed to perform some tasks was simply not present, so the technician could not effectively diagnose problems remotely (which negated the basic purpose of the MCC).

Based on the Goal-Directed Task Analysis, a prototype of a new system was developed. In this new system, information is oriented around the goals of the technicians, and information that was either missing or difficult to access in the old system is now made readily available. By better supporting the goals and related information needs of the technicians, the new system improves their ability to quickly discover and diagnose faults.

## CONCLUSION

We discussed three challenges in the domain of military Command and Control (C2), namely "smaller, better and faster", and reviewed three successful applications of Cognitive Engineering methods to address similar challenges in other domains. These three success stories provide a roadmap for applying the methods of Cognitive Engineering to problems in C2 Systems Engineering.

To address the challenge of reducing staffing levels (smaller), Computational Cognitive Modeling is useful for predicting human performance in the context of newly designed systems.

To address the challenge of improving coordination (better), Cognitive Work Analysis is useful for highlighting information that must be made visible to human operators so they can effectively monitor and control automated systems.

Finally, to address the challenge of decreasing execution times (faster), Goal-Directed Task Analysis is useful for assessing what information should be shared among the members of a team to facilitate more rapid situation awareness.

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