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INTEGRATING COGNITIVE ANALYSES INTO A LARGE SCALE SYSTEM DESIGN PROCESS

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This paper describes an approach for integrating cognitive analysis in the early stages of design of a new, large scale system -- a next generation US Navy Surface combatant. Influencing complex system designs in ways cognizant of human-system integration principles requires work products that are timely and tightly coupled to other elements of the system design process. Analyses were conducted, and recommendations made in parallel with, and as inputs to design decisions regarding system purposes, functionality, automation capabilities and staffing levels. We could not wait for design decisions to be made before proceeding or require other design groups to wait for our outputs. Thus, it was necessary to select and adapt cognitive work analysis methods to fit the demands of a time pressured design situation. A functional abstraction hierarchy model, and a series of cross-linked matrices were developed to provide a principled mapping between system function decompositions produced by system engineering teams, cognitive tasks, information needs, automation requirements, and concepts for displays. Cross-referencing the matrices supported design traceability standpoint and the integration of cognitive analyses with functional analyses being performed by other design teams. Results fed into design decisions with respect to level of automation, manning requirements and initial display prototypes. Providing an illustration of the processes and methods we applied is valuable because it describes and formalizes the relationship between concepts used in cognitive analyses and those used in systems engineering; it demonstrates the generalizability of cognitive engineering methods in a set of circumstances where few well documented examples exist; and it provides guidance for other human factors practitioners who may find themselves in similar circumstances.

INTRODUCTION

To date, there have been numerous scholarly articles and texts advocating the application of cognitive engineering methods to support the design of complex, human-machine systems. Such methods typically include in-depth data collection through interviews of domain experts and observation of practitioners; system, operator, and task modeling; and development of outputs oriented towards function allocation, design of interfaces to control and information systems, task definitions, and training requirements. The focus of cognitive engineering methods is on the identification of system and task demands that pose complexities for agents (human or automated) operating the system, and posing design solutions (e.g., interfaces) to mitigate those complexities. For example, Roth and Woods (1988) and Woods and Roth (1988) presented the development of competence and performance models which describe the constraints and demands posed by a complex process control system, and the competencies and strategies expert operators used to control the system, respectively, along with the application of those models to the development of design interventions to support operator performance. Vicente (1999) and Rasmussen, Pejtersen, and Goodstein (1994) present an extensive methodology of modeling and analysis which supports the derivation of display design requirements, information requirements, human-automation function allocation decision, and operator knowledge and skill requirements based on successive and iterative analyses of system and task constraints. Other methods in cognitive analyses (e.g., Hoffman, Crandall, and Shadbolt, 1999) have emphasized the use of interview techniques to elicit information regarding critical decision points, strategies, and information needs in the control and operation of complex systems in order to gather information to support design interventions.

In many cases, the application and utility of cognitive engineering methods have been demonstrated for systems in which the system to be controlled is reasonably well defined and for which some models and descriptions of system functions, automation capabilities, and likely operator tasks can be obtained. Cognitive engineering methods might be called on, for example, to aid in the redesign of the human-system interface for a newly automated system, or to develop an information system or decision aid to support a set of tasks where such support did not previously exist.

In contrast, this paper describes the application of cognitive engineering methods in the early stages of a design process of a new, large scale system – a next generation US Navy Surface combatant - in the face of a unique set of challenges. In particular, cognitive engineering methods were applied, and recommendations developed, both in parallel with and as intended inputs to design decisions regarding system purposes, functionality, automation capabilities and availability, and staffing levels. This led to difficult problems, such as the need to identify effective strategies for human-automation interaction in the context of a particular task, without a clear understanding of what functions could and would be automated, and how many operators would be available to support the function. Additionally, the cycle time for both required design decisions and iterations to those decisions was very rapid (sometimes on the order of weeks); precluding in-depth data collection and analysis methods.

Regardless of these difficulties, influencing complex system designs in ways cognizant of human-system integration principles requires inputs early in the design process, on a timeline often driven by a multitude of constraints. In our case, we could not wait for certain design decisions to be made before proceeding, and nor could we influence or schedule the sequence with which designs for system components were being formalized (that is, force other design groups to wait for our outputs). Thus, it was necessary to select and adapt cognitive work analysis methods and models as appropriate, to fit the demands of a time pressured design situation.

Providing an illustration of the processes and methods we applied is valuable because it describes and formalized the relationship between concepts used in cognitive analyses, and those used in systems engineering; it demonstrates the generalizability of cognitive engineering methods in a set of circumstances where few well documented examples exist; and it provides guidance for other human factors practitioners who may find themselves in similar circumstances.

SYSTEM DESCRIPTION

The system being designed was a next-generation US Navy Surface combatant. This particular ship had a primary mission of Land Attack (supporting land-based military operations); however, as a surface combatant it was also expected to support offensive and defensive air and undersea operations. A primary focus for the cognitive analyses was to support the design of watchstander tasks, functions, and support systems (e.g., controls and information displays) in the bridge and combat command center of the vessel. The analyses therefore focused on areas such as the Land-Attack Watchstander, Air and Surface Warfare Watchstander and Undersea Warfare Watchstander.

APPROACH

As a system being designed, the assignment of goals and functional roles specific to each watchstander position was still under consideration. Although watchstander functions could be modeled to a certain extent on prior naval operations, an expected reduction in manning (a primary design goal for this ship) required that the reassignment and combination of watchstander functions be considered. Additionally, the focus of the ship on the support of land based operations added the requirement for additional, new watchstander positions. Therefore, one goal of our analysis was to identify and document the likely goals and system functions associated with each warfare area, and therefore the corresponding watchstander(s). Also, as noted above, fundamental questions regarding the level of automation that would be both technologically feasible and reliably implemented were being addressed in parallel with our analyses; and staffing levels had not been determined (and in fact were going to be based on both the output of the cognitive analyses, and the decisions regarding automation levels). Therefore, a detailed analyses mapping goals to system functions, task responsibilities, and operator actions was impossible. Thus, our second primary goal was to identify higher level information needs associated with the potential functions, and to make recommendations regarding the allocation of certain functions between human watchstanders and automation based on principles of human-centered automation, rather than a formal task or functional analysis. The analyses of information and control needs were then used as input to form high level display concepts covering different functional areas. To perform these analyses, a variety of data collection, modeling and analyses methods were utilized, a subset of which are described below.

METHODS AND RESULTS

Data Collection

There were three primary sources of data available to us to perform the cognitive analyses: knowledge of domain experts, design documents being produced by other segments of the ship design team, and design requirements produced by the Navy. Due to a variety of constraints, it was not possible for us to conduct observational studies of operational naval vessels or training facilities.

The design documents included extensive textual and graphical representations of various potential concepts for how the ship would function and the roles it would serve under various operation contexts (e.g., while in support of ground troops; while transversing a mine field, etc.). Additionally, functional decompositions were being produced and refined to decompose high level system functions (e.g., defend against air threats) into more detailed sub-functions and tasks. These operational descriptions and functional decompositions were based in part on requirements for operational functionality imposed by the Navy.

In addition to reviewing design documents, our primary data source was interaction with domain experts. This interaction took two forms: formal interviews lasting from approximately 2 to 3 hours with ex-Navy and Marine officers, and on-going discussions and contributions from ex-Navy officers who were part of the cognitive analysis team. The formal interviews were semi-structured in nature, and were based on sets of probe questions related to the cognitive analyses goals of identifying system complexities, and requirements for successful system operation. One set of questions used earlier in the analyses process focused on eliciting system goals, expected functionality, and ship systems, while a second set of questions focused on eliciting information regarding command and control tasks and decisions associated with different warfare areas. Access to two domain experts as part of the cognitive analysis team allowed continued refinement of our understanding of ship operations, possible watchstanding configurations, and organizational and cultural factors which could influence our recommendations.

Abstraction Hierarchies

As a first step in understanding system complexities, we constructed a Abstraction Hierarchy (AH) of a subset of the ship and its systems. Abstraction hierarchies, used to describe work domains, consist of multiple models of a system's goals, functions, and physical instantiation, linked by means-ends relationships. In practice, abstraction hierarchies are frequently supplemented with orthogonal part-whole hierarchies describing system decomposition (for a complete description, see Bisantz and Vicente, 1994 or Vicente 1999). Implementation of the AH was completed using the Work Domain Analysis Workbench (Sanderson et al. 1998), a software tool which supports the construction of abstraction hierarchy models. We exploited features of the software to highlight nodes related to different high level goals in different colors, and to annotate links and nodes where possible interactions or mutually constraining factors were present. For example, Figure 1 shows a small portion of the AH that was created, illustrating means-ends relationships between general functions like the need to maintain awareness of the battlespace, and physical systems which accomplish that function (e.g., sensing systems); part-whole relationships between sensing systems overall and more specific sensing systems; and links reflecting the mutual constraints such as the fact that environmental (oceanic) conditions impact the effectiveness of undersea sensors, which in turn affect the ship maneuvers that need to be undertaken to continue to track a possible contact.

The AH model was related to the functional decompositions at the level of generalized function (the top level shown in Figure 1). Higher level functions from the decomposition were mapped to nodes at the level of generalized function.

The construction of the AH accomplished three goals:

- It clarified of our understanding of the ship systems, and provided a vehicle for knowledge elicitation from the domain experts on the cognitive analysis team
- It demonstrated to other design groups how a goal oriented functional analysis (the AH) mapped to the functional decompositions they were creating.
- It highlighted resource constraints and interactions between and within warfare areas that would need subsequent attention in the design of displays and communication channels.

System Function Mappings

A substantial portion of our effort was spent developing principled mappings between system functional decompositions being provided by system engineering design teams, cognitive tasks, information needs, automation requirements, and concepts for displays. To accomplish these mappings, we developed and populated a series of cross-referenced matrices based first on the system functional decomposition. Information contained in the matrices was derived from the formal interviews as well as extensive inputs from the domain experts on the cognitive analysis team.

First, for each system function, informational requirements for primary monitoring and operational requirements, requirements for access to detailed information, an indication of a need for manual operation and override, and any assumptions were identified and described. For example, Figure 2 shows an example set of entries corresponding to the system function “Filter tracks” (e.g., determine which of many entities such as ships, planes, etc. are shown on the display) for Land Attack Warfare. These matrices were completed for functional decompositions of several different warfare areas. To give an idea of scale, the functional decomposition for Land Attack Warfare consisted of over 300 different functions and sub-functions which were analyzed in this way. During this process, it became apparent that the cognitive functions of the watchstanders were not explicitly represented in the system decomposition. Thus, to augment the first system matrix, a second, cognitive function matrix was developed listing explicitly the cognitive tasks required of the watchstanders in the accomplishment of system goals (see Figure 2). This matrix had nineteen entries including specific needs for system monitoring, maintaining situation awareness, monitoring goal achievement, and communications, and was cross-referenced to the system matrix to explicitly show the relationship between the system functions and cognitive functions needed to support them. Finally, concepts regarding information displays across system functions were combined and categorized into a set of display areas which were cross-referenced to the cognitive function matrix. Eleven display areas for Land Attack Warfare support were identified, including the Local Area Picture shown in the example, Task Scheduling and Status Area, Tactical Picture area, Communications area, and others.

Completion of these matrices provided inputs to design teams regarding the appropriate operator role vis-à-vis different possible automation alternatives; high level information requirements to allow human support of system functions; the explicit cognitive functions requiring support, and general concepts for display designs to support watchstanders in different warfare areas. Cross-referencing the matrices was important from a design traceability standpoint, and to integrate the informational, display, and cognitive analyses with the functional analyses being performed by other design teams. Ultimately, descriptions of the display design areas were used to support the design of initial display prototypes.

SUMMARY

This paper describes the application of cognitive engineering principles and methods to the design of a large-scale, complex system. The methods and analyses described are valuable because they show how models and analyses can be adapted and applied early in, and concurrently with, the overall system design process.

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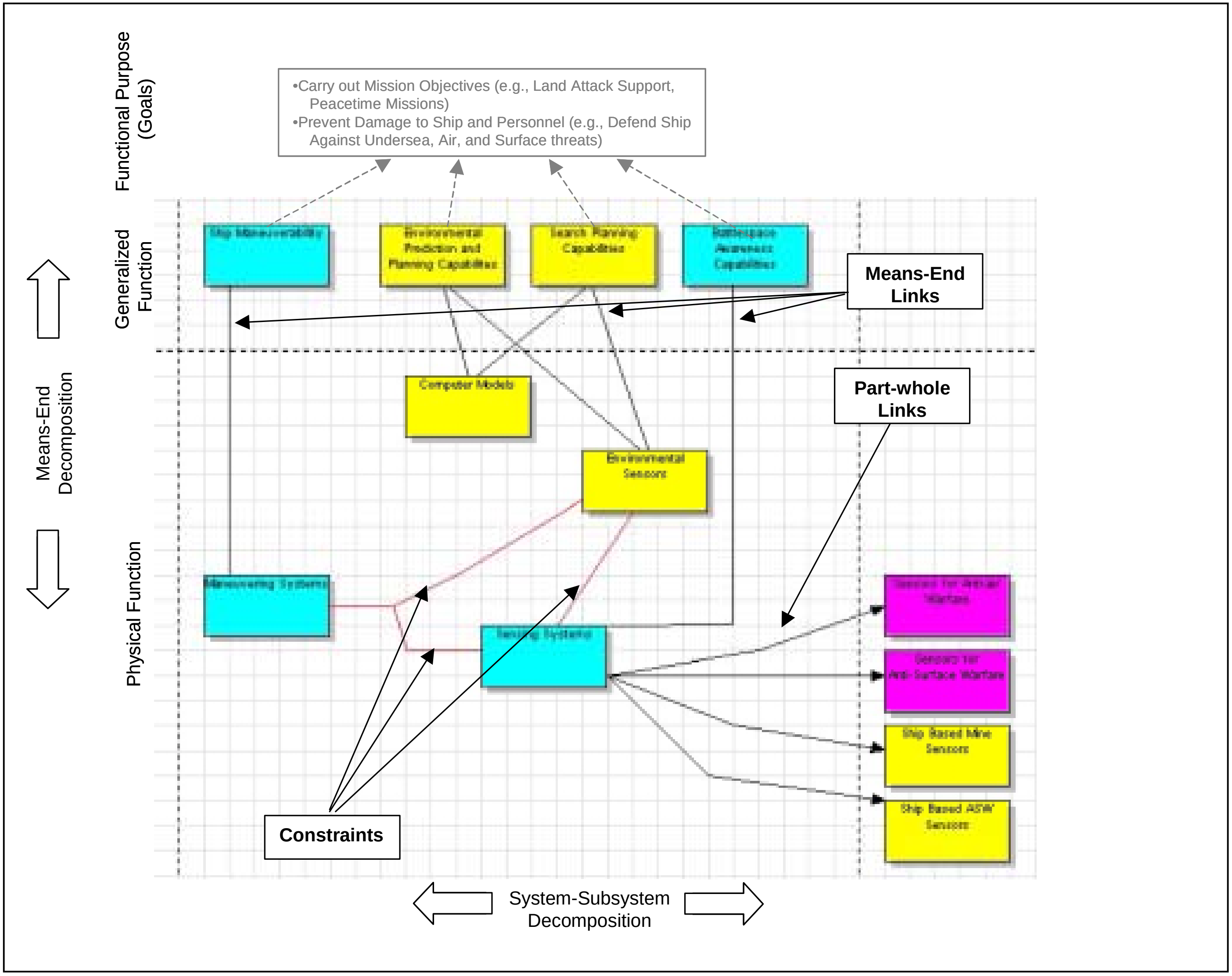
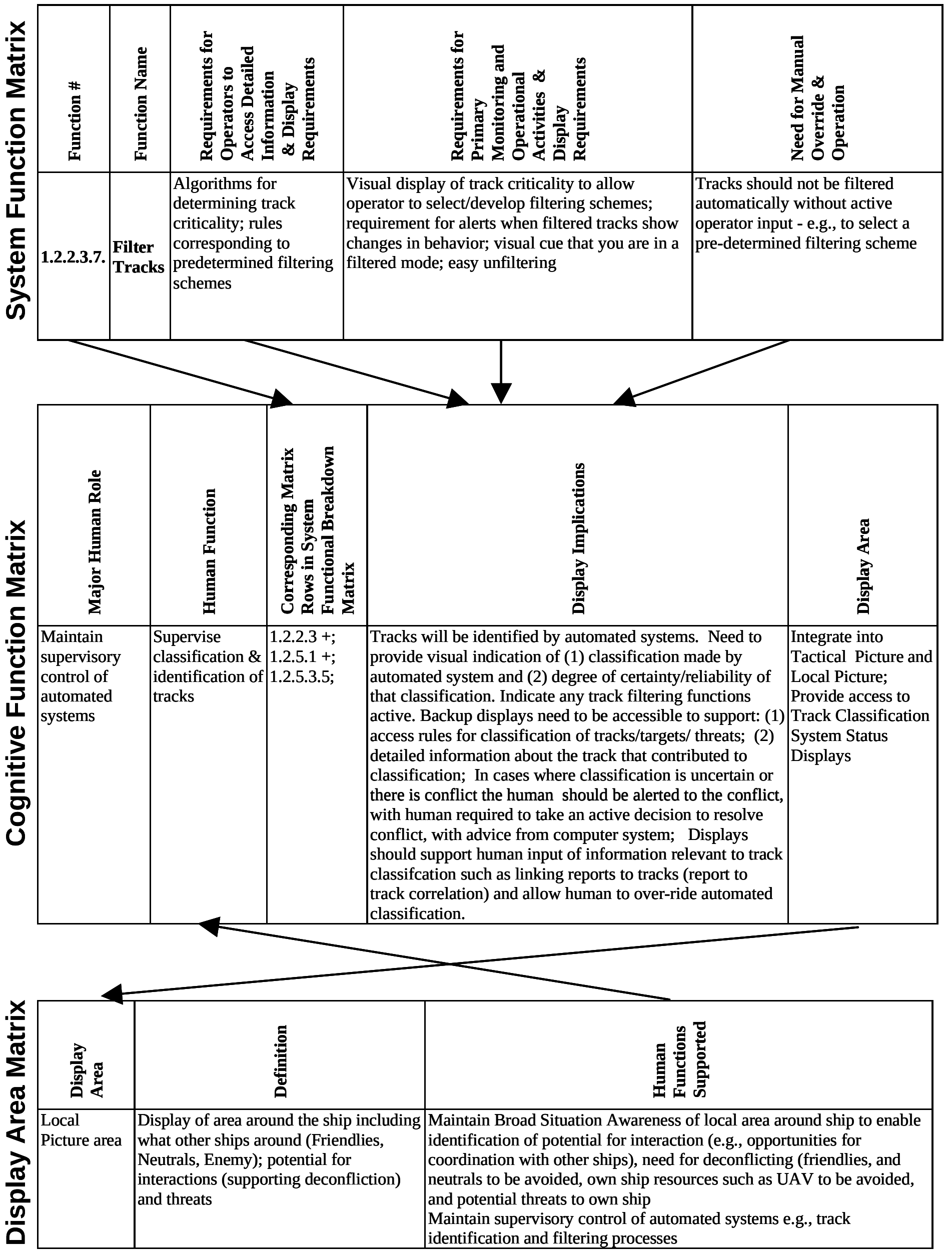
Figure 1. Portion of the AH model developed. Means-end, part-whole, and constraint links are labeled; dashed lines indicate a transition between means-end or part-whole levels. For clarity, a sample of top level goals is shown in gray; these goals were linked through a variety of other nodes, means-ends, and part-whole links (not shown in the figure) to the nodes shown. WDAW was used to



create the AH. Clicking on constrain links allowed a description of the constraints to be entered and accessed.

Figure 2. Example Entries from the System Function Matrix, Cognitive Function Matrix, and Display Area Matrix showing entries and relationships between the matrices. Only one entry of many from each matrix is shown.



System Function Matrix

Function #	Function Name	Requirements for Operators to Access Detailed Information & Display Requirements	Requirements for Primary Monitoring and Operational Activities & Display Requirements	Need for Manual Override & Operation
1.2.2.3.7.	**Filter Tracks**	Algorithms for determining track criticality; rules corresponding to predetermined filtering schemes	Visual display of track criticality to allow operator to select/develop filtering schemes; requirement for alerts when filtered tracks show changes in behavior; visual cue that you are in a filtered mode; easy unfiltering	Tracks should not be filtered automatically without active operator input - e.g., to select a pre-determined filtering scheme

Cognitive Function Matrix

Major Human Role	Human Function	Corresponding Matrix Rows in System Functional Breakdown Matrix	Display Implications	Display Area
Maintain supervisory control of automated systems	Supervise classification & identification of tracks	1.2.2.3 +; 1.2.5.1 +; 1.2.5.3.5;	Tracks will be identified by automated systems. Need to provide visual indication of (1) classification made by automated system and (2) degree of certainty/reliability of that classification. Indicate any track filtering functions active. Backup displays need to be accessible to support: (1) access rules for classification of tracks/targets/ threats; (2) detailed information about the track that contributed to classification; In cases where classification is uncertain or there is conflict the human should be alerted to the conflict, with human required to take an active decision to resolve conflict, with advice from computer system; Displays should support human input of information relevant to track classifcation such as linking reports to tracks (report to track correlation) and allow human to over-ride automated classification.	Integrate into Tactical Picture and Local Picture; Provide access to Track Classification System Status Displays

Display Area Matrix

Display Area	Definition	Human Functions Supported
Local Picture area	Display of area around the ship including what other ships around (Friendlies, Neutrals, Enemy); potential for interactions (supporting deconfliction) and threats	Maintain Broad Situation Awareness of local area around ship to enable identification of potential for interaction (e.g., opportunities for coordination with other ships), need for deconflicting (friendlies, and neutrals to be avoided, own ship resources such as UAV to be avoided, and potential threats to own ship Maintain supervisory control of automated systems e.g., track identification and filtering processes