The solution for future command and control: human-centered design

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ABSTRACT

The only way to deal with the increased complexities of the future in command and control, the huge amounts of data available, reduced manpower and cost goals, and training in tactical operations is to follow a human centered design process. It is time we design the hardware/software system to support the people instead of asking the people to compensate for the hardware/software system. This will only be accomplished by institutionalizing an integrated human systems engineering process that fully accounts for every person in the system. Use of this process will be critical to future complex system designs and in particular to integrated command centers. In addition to engineers following the process, engineering environments must facilitate a human systems engineering approach. A human systems engineering process and a prototype engineering environment, the Human Centered Design Environment which is currently under development, are described.

Keywords: Human Engineering, Systems Engineering, Human Systems Engineering, Command and Control, Human Centered Design, Human Centered Design Environment

1. INTRODUCTION

In the post-Cold War era, the United States Navy is dealing with down-sizing, decreasing budgets, new and expanding missions, and lower retention rates for sailors. The Navy has expended a significant effort investigating the cost of "manning" its ships. Manpower related costs are estimated to be as much as 60% of the budget. Learning from the experiences of foreign navies and our own industries, full automation is not always the answer, especially where automation has been introduced to existing systems and platforms rather than new construction. Automation is extremely expensive, particularly in systems which are highly complex and deal with often ambiguous data. For example, automating the command and control functions of a warfighting ship may not result in reduced workload. Operators may have a difficult time maintaining situation awareness in these highly automated systems of systems. Cognitive workload may actually be increased as operators strive to understand the actions or analysis the system has performed.

In addition, at the Navy Safety Center, the U.S. Coast Guard, and the International Maritime Organization, data indicates that as much as 80% of ship accidents are caused by errors attributed to personnel. During and after at-sea qualifications of incredibly complex systems, failures are often written up as "operator errors – system [hardware and software] performed correctly."[1] This indicates the widely held concept that the system consists only of hardware and software.

In May 1999, the Director of Surface Warfare (N86) for the U.S. Navy exhorted the ship systems development community to change "the way we design our ships and installed systems by institutionalizing human centered design, human systems integration, and detailed front end analysis of all manpower and training requirements."[2] Much effort is underway in the Navy and its support infrastructure that will answer this call.

One such effort, the Office of Naval Research (ONR) SC-21 Science and Technology Manning Affordability Initiative (MAI), is developing and providing, amongst many offerings, a well-defined human systems engineering process and a Human Centered Design Environment (HCDE). The MAI is jointly managed between ONR and the DD21 Ship Program Office, and provides a unique opportunity for partnership between operational, design, and science and technology

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organizations within the Navy community.[3] For more information on MAI, see www.manningaffordability.com The human systems engineering process defined by MAI addresses issues which relate to systems that include humans, while fully incorporating all the traditional aspects of the systems engineering process.

1.1. Background

Systems engineering is a structured, collaborative approach that incorporates multiple engineering disciplines to methodically develop a balanced life-cycle system solution that meets the customer's requirements. Human Factors Engineering is a discipline that accounts for the capabilities and limitations of the human and applies these to the design of systems. In the past, human factors engineering issues were not well integrated within system engineering design efforts. Where human factors engineers are called upon, it is usually late in the design process, or even post design. Therefore, human factors engineering solutions are often not implemented due to the increased cost of late design changes. Design deficiencies become the operator's problems and may require high skill levels to overcome these deficiencies. These skill requirements drive increased training demands, potential user availability problems, and increased system failures or errors. Exacerbating this problem is the rate of technological change that levies significant constraints on system development time. Program managers are pressured to maintain schedules which frequently result in premature allocation of system functions when the requirements are not yet defined, or functional allocations are not adequately optimized. Late design changes are considerably more expensive, reducing the probability that they will be approved, even when necessary.

Systems engineers are not always familiar with the issues of human-system integration. Systems engineering processes have emphasized hardware and software issues, leaving human systems issues scantily addressed. Human factors engineers/engineering psychologists and systems engineers also speak different technical languages. A process articulated in a common language is required to bridge this gap. In addition, an integrated design environment that supports this process must be available.

In order to support the development of systems that are optimized for use by human operators, the S&T/HCDE program team recognized the need to inject human user considerations within appropriate activities of the system development process. It was critical that the process be one ascribed to and used widely by systems engineers. The human user considerations that this effort would insert into mainstream system engineering processes are much more profound than the usual Man-Machine Interface (MMI) consideration. These considerations are absolutely critical to proper trade-off of functions among operators and system components throughout the development process. Under the S&T/HCDE project, a human systems engineering process has been established with the objective to enforce the consideration of human aspects as part of the total system design process. The HCDE team has successfully negotiated the inclusion of this human engineering process into the update of the IEEE 1220 System Engineering Standard, a commercial systems engineering standard, promulgated in October 1998.[4]

"Human Systems Engineering" is defined as the activities involved throughout the system life cycle that address the human element of system design" (IEEE 1220, 1998). These activities include the definition and synthesis of manpower, personnel, training, health hazards, safety issues, human factors, and any other issues addressing human activity within the system. This concept of the human systems engineering process, while consistent with traditional definitions of human factors and human systems integration, fully imbeds human engineering into the systems engineering process and employs common terminology.

Effective implementation and execution of the human systems engineering process requires the collaboration of a team of systems engineers, human factors engineers, and application domain experts. These in turn need to be supported by common methods and tools. The sharing of semantic as well as syntactic information between the members of the team as well as their tools of choice is enabled by a common database schema that provides a consistent structure and format for information exchange.

An initial human systems engineering data base schema has been implemented in an integrated tool environment developed under the Manning Affordability Initiative. This environment is a mix of primarily commercially available systems engineering and human factors engineering tools along with tools developed by the program.

2. HUMAN SYSTEMS ENGINEERING PROCESS

2.1. Human Systems Engineering.

To achieve the desired impact, human systems engineering must be fully integrated with systems engineering. Human systems engineering products must be the result of a disciplined engineering effort that is conducive to overall system analysis. To meet these needs, the human systems engineering framework was modeled after typical systems engineering practices. Multiple sources of human factors process descriptions were evaluated. Key documents included the ShipSHAPE process[5], the NATO panel research group's report on Analysis Techniques for Man-Machine System Design[6], Human Factors in Systems Engineering[7] and an HFES Conference Workshop on human factors methods[8]. Leveraging process descriptions of human factors engineers ensured that the process defined in the systems engineering framework would be true to the problems and issues it is intended to solve.

As depicted in Figure 1, the human systems engineering process follows the basic top-down systems engineering framework. The six major steps of the human systems engineering process are mission analysis, requirements analysis, function analysis, function allocation, design, and verification. The following sections define and describe the major steps of this human systems engineering process and provide examples of methods that are applicable to that design step.

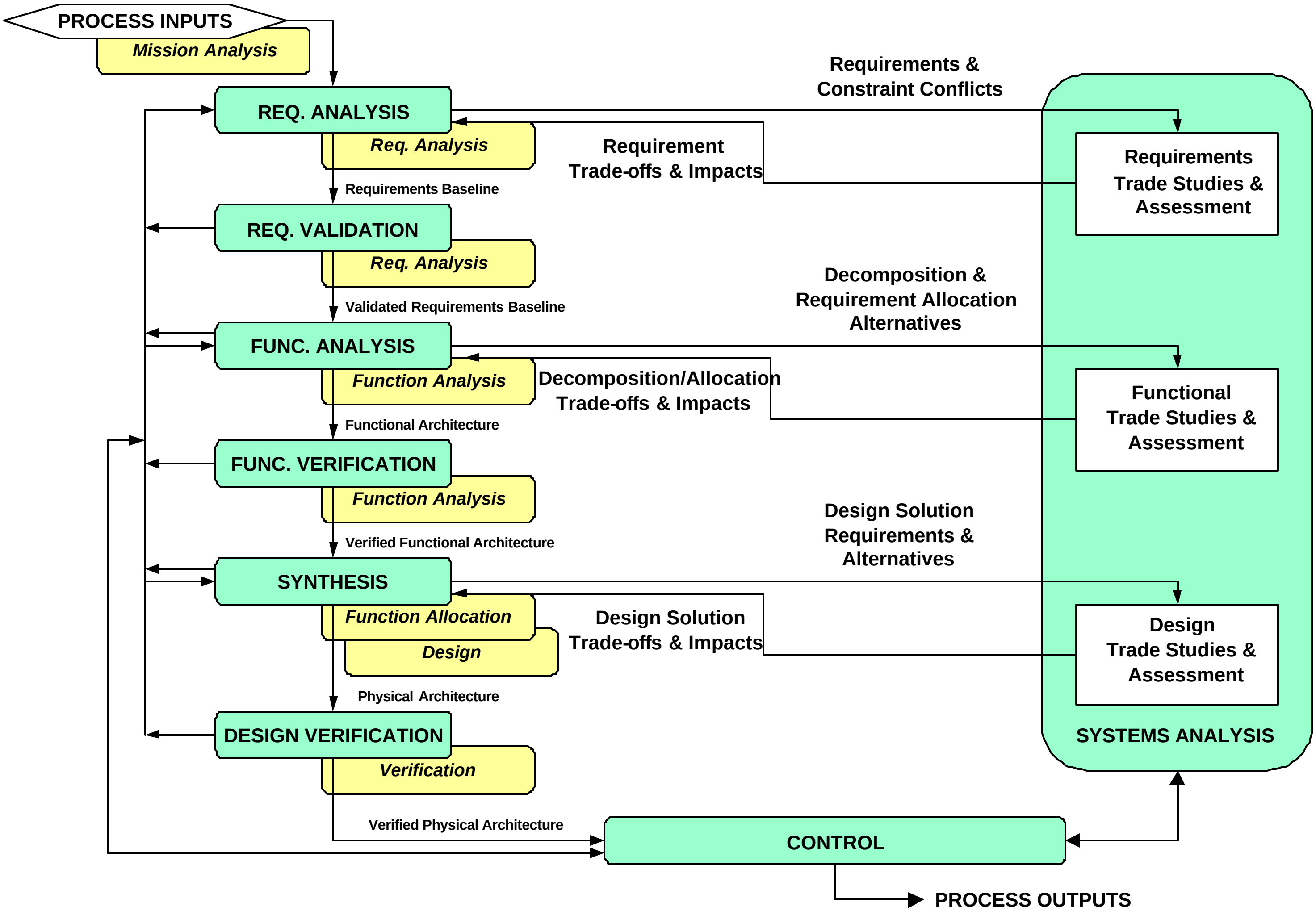

Figure 1. Human Systems Engineering Process and Systems Engineering Process of IEEE 1220-1998

In addition to consistency with the systems engineering process, the human systems engineering process must be consistent with its heritage in human factors engineering.

2.2. Mission Analysis.

The start of a system engineering effort is mission analysis, where the overall system purposes, objectives, capabilities, operational environments, and basic functions are determined. Mission scenarios are identified or created. The focus is on the definition of the system boundaries, treating the system as a "black box" and defining inputs, outputs, environments, and other constraints.

To articulate the mission, narrative mission descriptions and graphic mission profiles can be employed as illustrated in Figure 2. Narrative mission descriptions detail the mission in terms of the characteristics, sequences and times of mission events, mission constraints, and environmental conditions. Details of the description facilitate identification of top-level functions required of the system. Graphic mission profiles illustrate the sequence of events that will determine the performance requirements of the system.

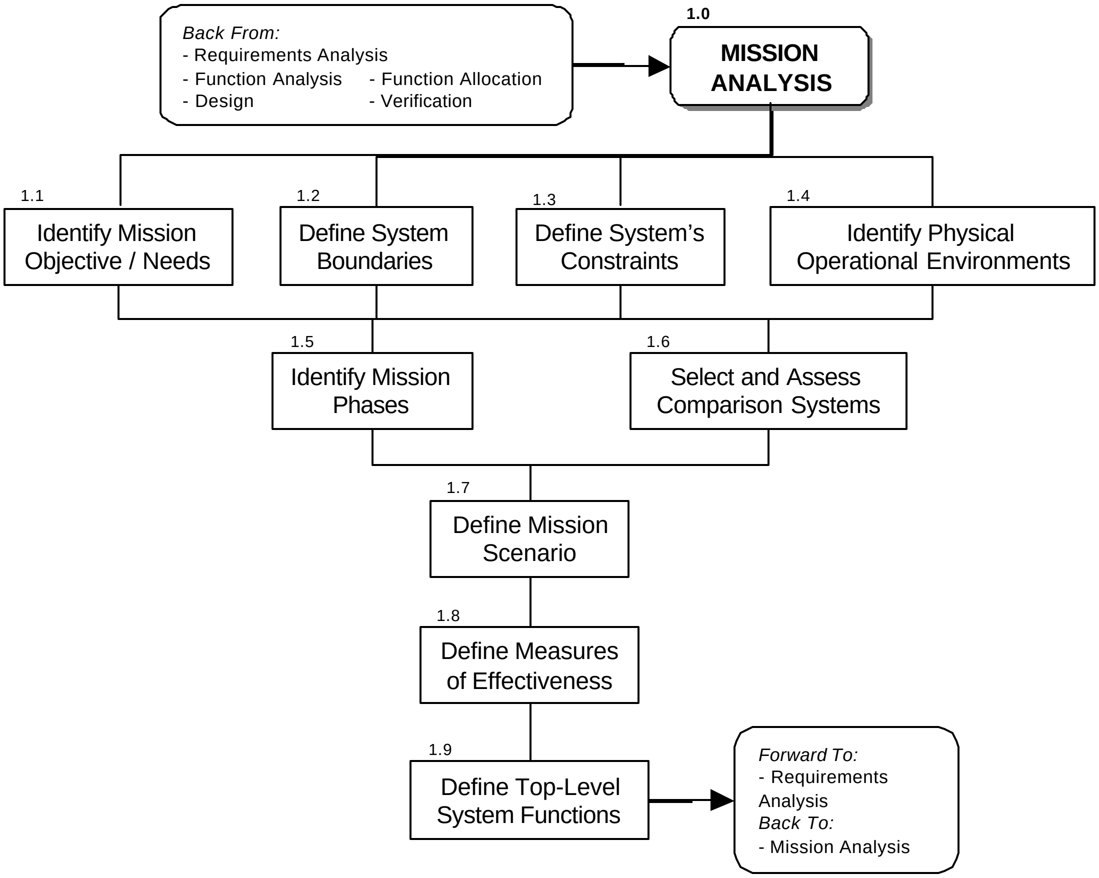

Figure 2. Mission Analysis Steps

2.3. Requirements Analysis.

Requirements analysis as shown in Figure 3, is performed to identify the characteristics of the system necessary to meet mission requirements. Intended users and maintainers of the system and activity-related needs of users are determined. The feasibility and internal compatibility of the system requirements are assessed. Measures of effectiveness and measures of performance of the mission, human and job/task requirements are defined. In this step, the role of the human, and manning, training, and cost guidelines are also developed.

2.4. Function Analysis

Function analysis output as identified in Figure 4 supports development of the system's functional architecture, the sequence of operations or events that turn inputs into desired outputs, and compares design alternatives. Although the system may be broken into functions, tasks, and subtasks to be performed, these tasks are not allocated to any particular system component.

This step and the three following steps are initially performed at a high system level with little function decomposition, but are iterated to greater levels of detail.

Function flow diagrams and behavior graphs are methods to analyze system functions. Function flow diagrams depict the sequential relationship of the system functions. This method logically inventories the system functions and structure. Behavior diagrams describe system behavior of control and information flow and scenario modeling, providing a complete behavioral model of the system.

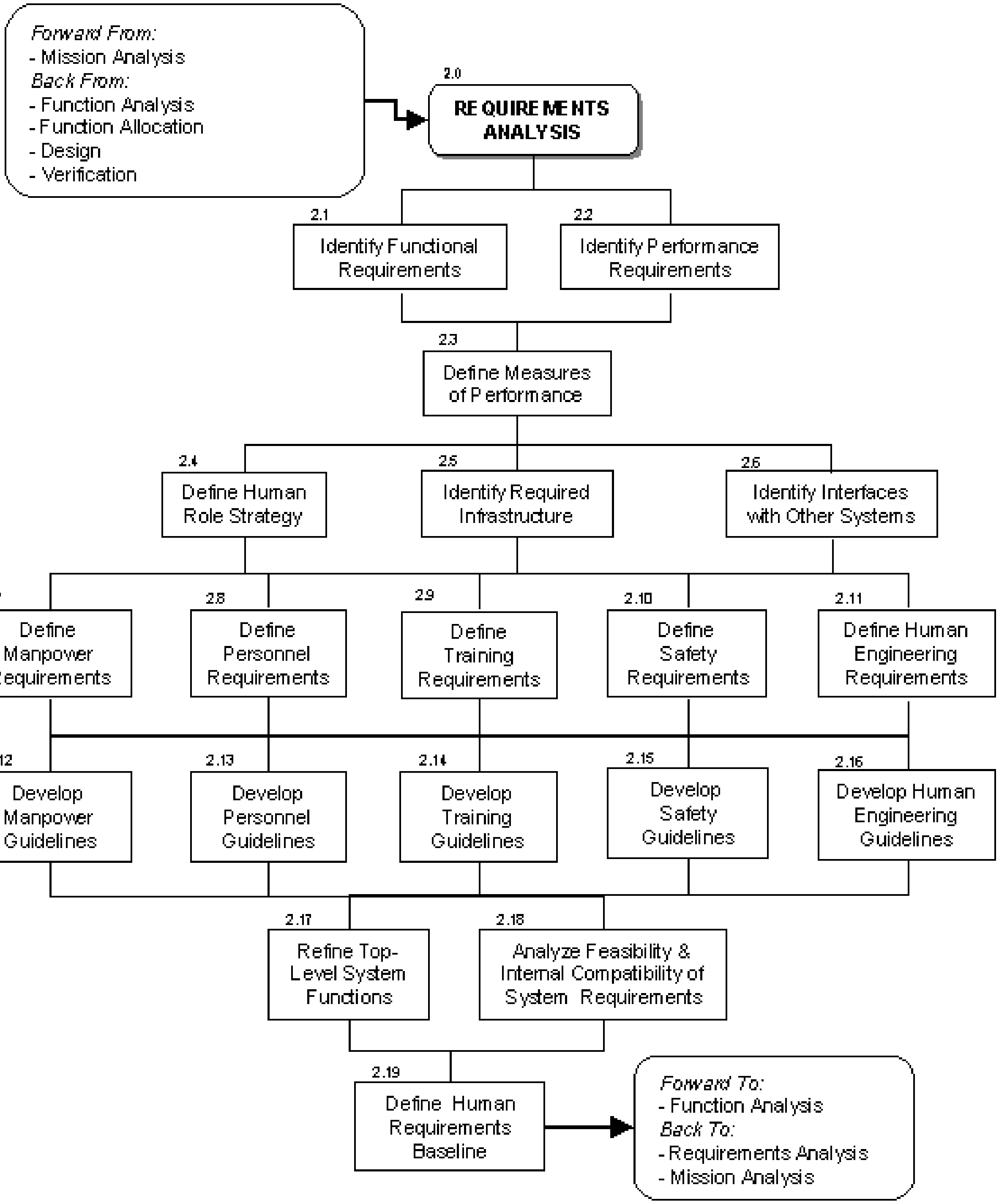

Figure 3. Requirements Analysis Steps

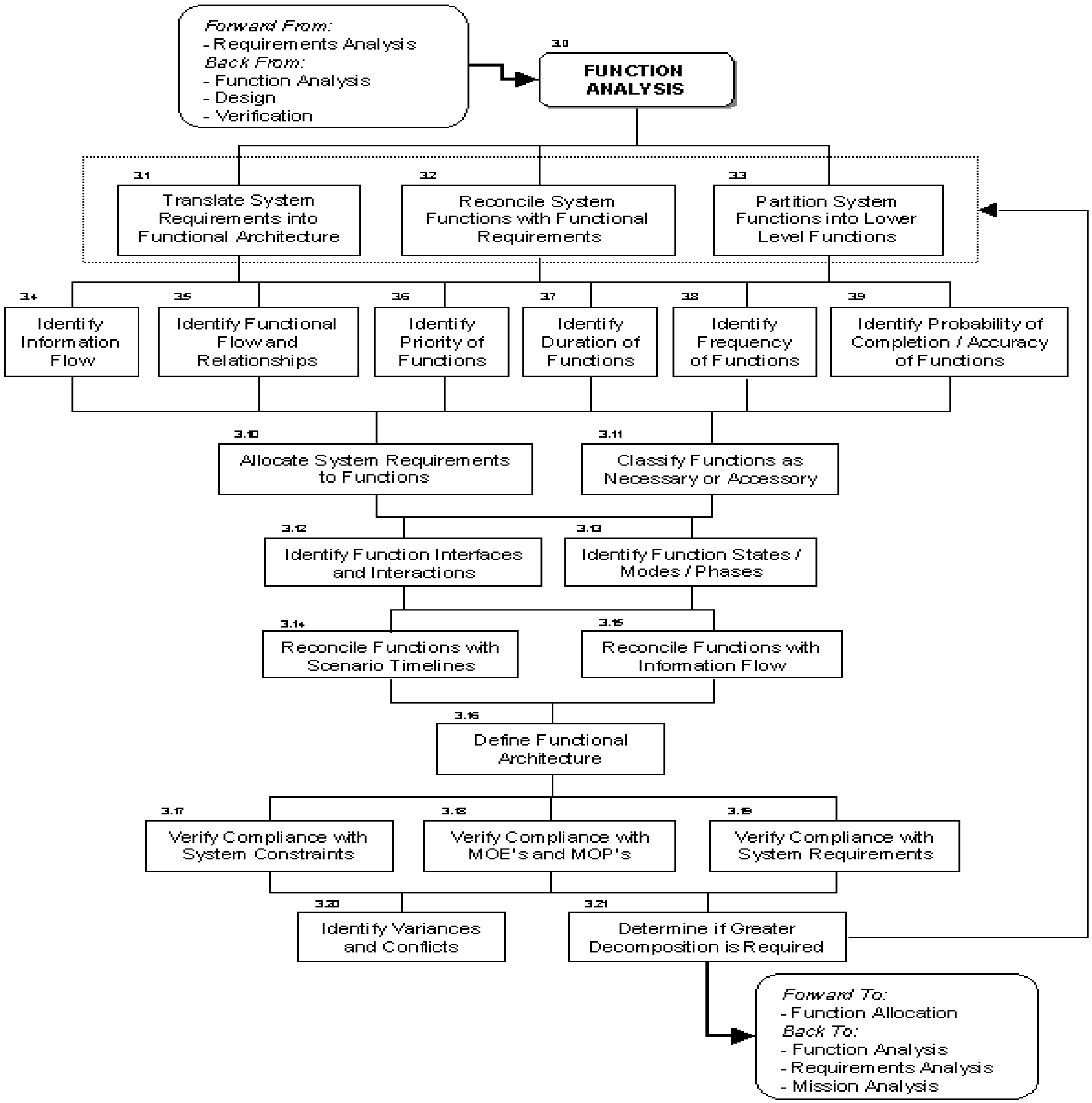

Figure 4. Function Analysis Steps

2.5. Function Allocation

Figure 5 illustrates that a critical step of the human systems engineering process is determining what functions are to be performed by humans. Function allocation distributes the defined functions among available resources (humans, hardware, software, or combinations). The allocation of some functions will be mandatory and predetermined by constraints established in the Mission Analysis or Requirements Analysis steps of design. Allocation decisions are determined by a comparison of performance among humans, hardware, and software; cost factors; anticipated operator workload; and cognitive support for the operators. Allocation decisions should be made to maximize total system performance and effectiveness. Allocation of a function may require redefinition of its component subfunctions. Function allocation will be guided by information requirements and decisions required to initiate, sustain, and otherwise support mission functions. How these allocation decisions impact total system performance is determined and adherence to defined requirements is assessed.

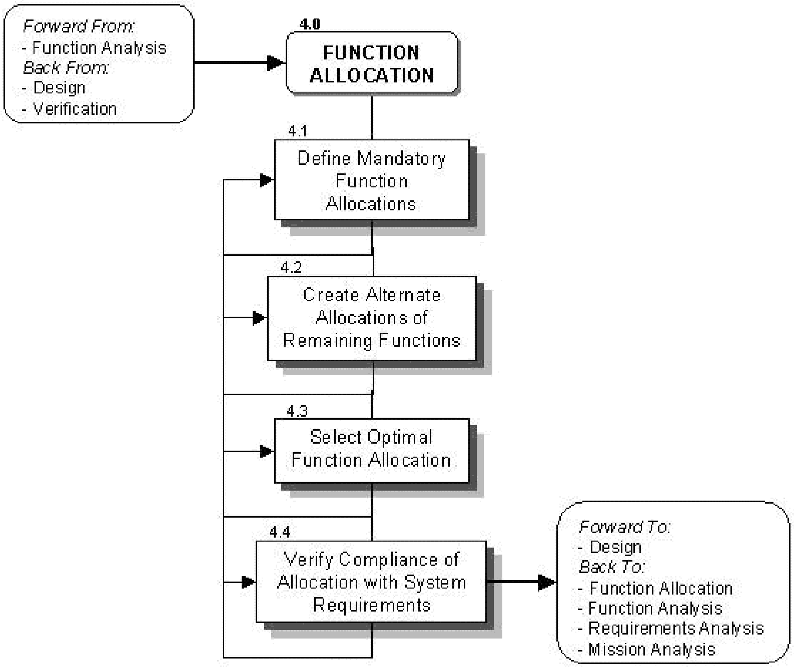

Figure 5. Function Allocation Steps

Function allocation has been aided with guidelines to assess human capabilities and function requirements, such as “Fitts’ lists” and evaluation matrices. While these guidelines are helpful, they can be dated and must be used judiciously.

Today’s technology affords us far more automation potential than in the past, but it comes with a cost. With automation comes a certain degree of cognitive distancing between the operator and the task; therefore, this automation must be applied carefully. Methods to support this step rely heavily on the engineer and designer and are not well automated themselves. This is an area ripe for more research and development of standardized methods.

2.6. Design

This step, as illustrated in Figure 6, is where the bulk of human factors and ergonomics methods have traditionally focused and where the majority of human system issues is resolved. A time-based description of the allocated system architecture must be defined, and interactions between tasks, and between humans and equipment examined. The flow of information and objects between components of the system is defined. The architecture is analyzed and functions and tasks are redefined as necessary. Determination is made as to whether or not the specified levels of activity (physical, cognitive, and temporal) for humans and equipment can be met with projected or currently available resources. Once the functional architecture meets mission and system requirements, operator interfaces may be specified and designed. Changes made to the functional architecture at this step will require a return to earlier steps to ensure that all system/mission requirements will be met.

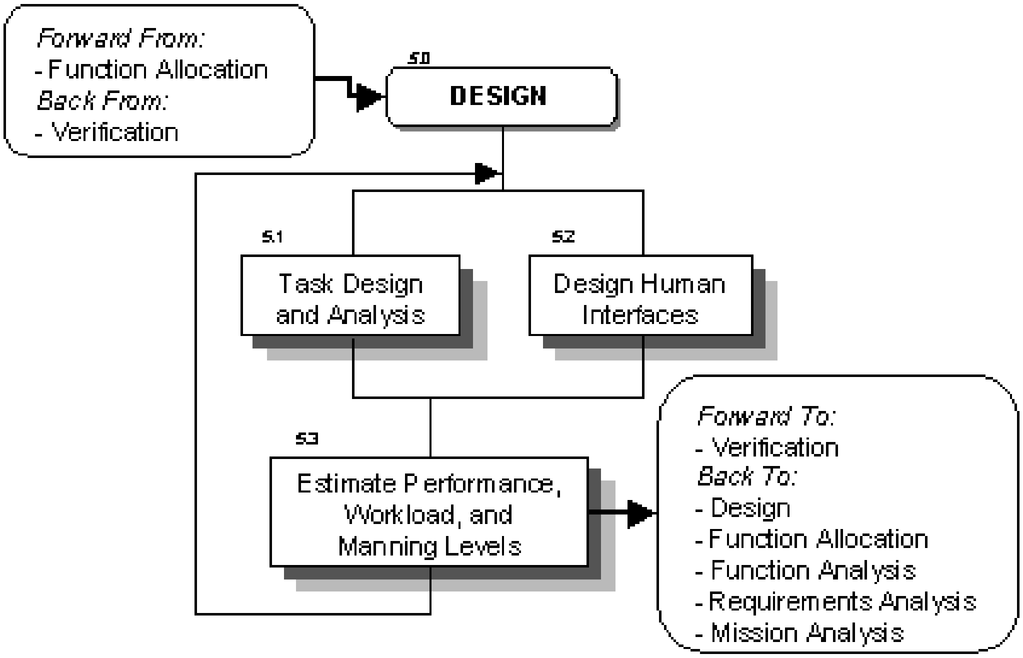

Figure 6. Design Steps

2.7. Task Design and Analysis

Human tasks required to ensure successful completion of the function are developed in terms of cues required to alert the human that a decision or action needs to be taken, the decision or action to be made, the information required to support the decision, and mechanisms to implement the results of the decision or action. The critical characteristics and interactions are also articulated. In addition to supporting other steps of the human systems engineering process, Operational Sequence Diagrams (OSDs) and Critical Task Analysis (CTA) methods are excellent tools for task definition and analysis.

2.8. Human Interface Design

Interfaces between humans and hardware, software, and other humans are designed such that physical and procedural interfaces are considered. Link analysis and design option decision trees facilitate this sub-step of design.

2.9. Performance, Workload, and Manning Level Estimation

Physical (perceptual, psychomotor, physiological, etc.) and cognitive workload levels for individuals and teams are estimated to provide approximate system performance. Workload stressors and their effects on human performance, operator coping strategies, and the effects of the task neglect/delay are defined. Workload and the resultant manning and training requirements should be optimized to meet required performance levels. Task network models and simulation provide mechanisms for early assessment of system performance with the defined human role. Subjective workload ratings during prototype testing also facilitate performance evaluation.

2.10. Verification

The potential performance of the system with respect to its ability to achieve required levels of operation is assessed as shown in Figure 7. Verification may be carried out either during conceptual stages using analytical or executable system models or after a physical prototype or mock-up has been constructed using human-in-the-loop simulations. Verification of some system components may be concurrent with design of other components. If the system under design is unable to achieve the required levels of performance and operation, then the requirements must be altered or the design improved through re-allocation of functions or selection of an alternate design. Storyboarding with subject matter experts, followed by prototype usability testing, will help verify the system meets its requirements. Early in system design, modeling can be employed to assess the design; however, it is critical to conduct human-in-the-loop testing of the system to fully verify the design.

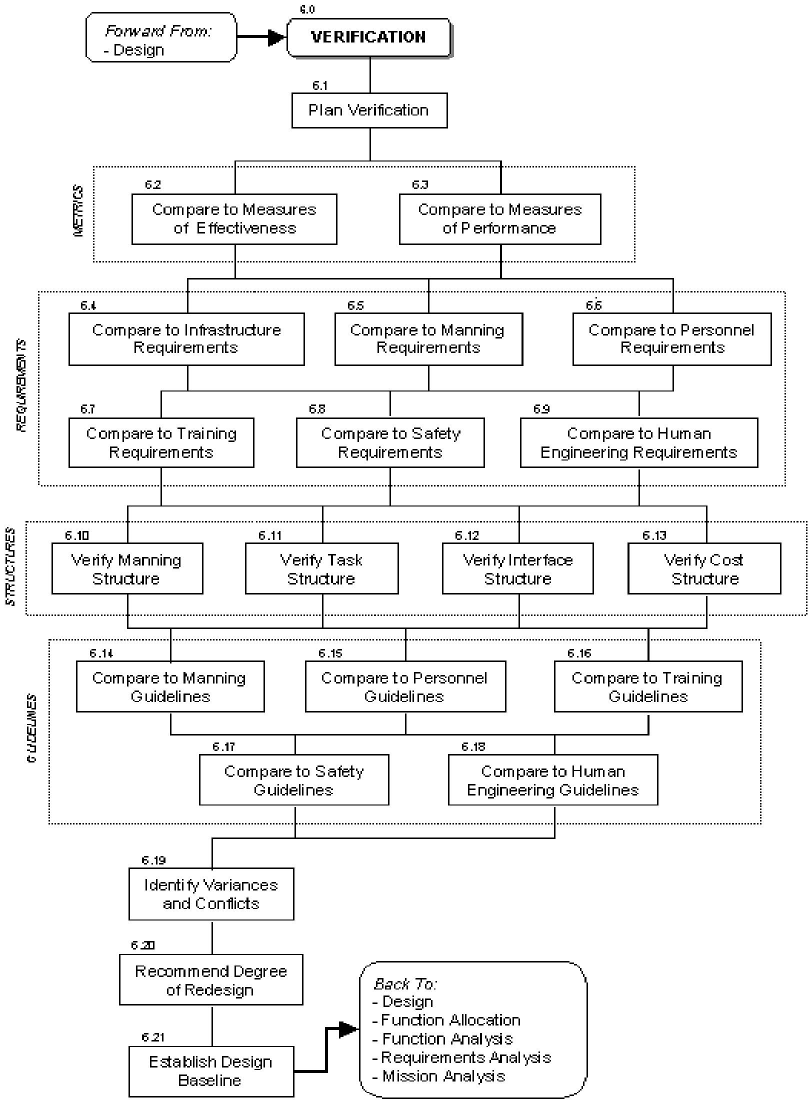

Figure 7. Verification Steps

3. HUMAN CENTERED DESIGN ENVIRONMENT

Process alone will not ensure a system is designed with the human element tightly integrated. Support must be provided to the diverse engineering team through the use of an integrated and advanced engineering environment in order to conduct the requisite complex analyses across the hardware, software, and human aspects of the design. The HCDE has established an approach and has developed an initial prototype environment to demonstrate such capabilities. The foundation and framework for this environment is a set of prototype system engineering capabilities developed under the Engineering of Complex Systems (ECS) Technology Program, sponsored by ONR. These capabilities include requirements capture and analysis, system architecture capture and analysis, and design evaluation and optimization. In addition, mechanisms for implementing a consistent, integrated systems engineering product and process management schema has been developed.

Advanced systems engineering environments which support the full systems engineering process, such as the HCDE, also facilitate communication and integration while reducing design costs and errors by removing the need to translate system design data between disciplines and automatically flagging design changes and notifying the appropriate personnel. For example, if a member of a design team makes a design change, the environment automatically notifies the human systems engineer that a design change has been made affecting the human systems analysis. Human systems engineers would then simply access the repository and open the design in their own specialty tools. After running the analysis on the modified design, the output would be instantiated in the repository making it accessible to the systems engineering team and the appropriate team members would be flagged. In this way, design changes are communicated more quickly and, as studies show, earlier changes cost far less.

3.1. HCDE Configuration

The HCDE prototype includes representative tools for each phase of the process, providing capabilities to support the entire system design process. These tools include both commercial-of-the-shelf products and research prototypes. The capabilities of HCDE will be extended and tested over the next two years.

Figure 8 illustrates the anticipated HCDE final product. This environment will provide an integrated framework to enable the following engineering activities:

- Requirements capture and analysis
- System functions capture and analysis
- System architectures capture and analysis
- Domain specific assessment (e.g., cost analysis, human task analysis, reliability analysis, etc.)
- Design trade-off based on closed-loop optimization
- Life cycle traceability

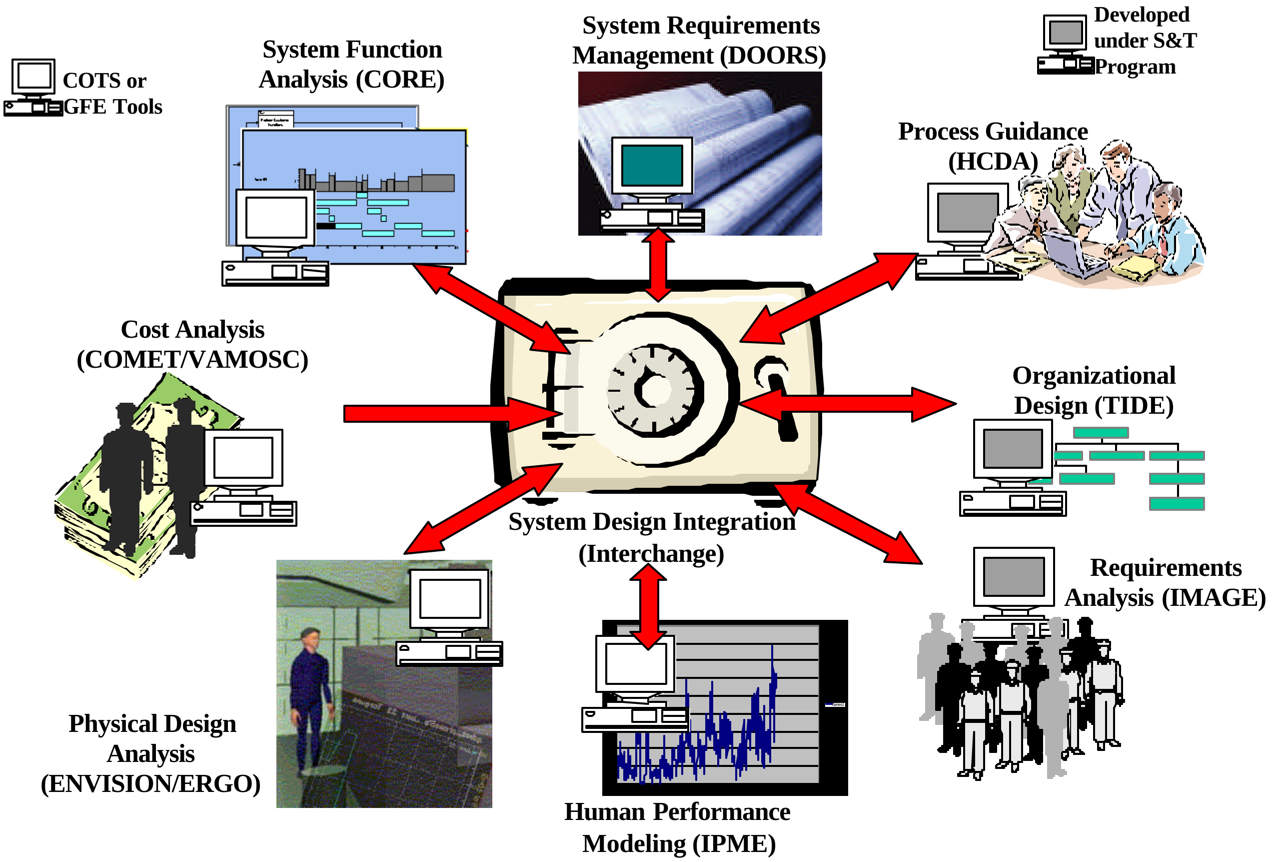

Figure 8. Human Centered Design Environment

The current prototype HCDE includes several commercially available engineering tools. Several "plug-ins" have also been developed to facilitate the transition of project data between the domain specific tools and the design repository. All copyrights and trademarks of each tool's respective company govern the following description of each of the currently integrated tools. The use of the commercially available tools described below does not in any way imply explicit endorsement of the tool, but rather a representative capability.

- *DOORS* (product of Quality Systems and Software Incorporated): Provides for managing requirements throughout development life cycles.
- *CORE* (product of VITECH Corporation): Provides automated solutions for requirements analysis and management, behavior analysis, architecture synthesis, and resource allocation, while ensuring design traceability and verification.
- *IPME* (product of Micro Analysis and Design Corporation): Focuses on simulation of humans, and human performance, in different environments through the use of task networks, operator models, environment models, performance-shaping models, and external models (interface for communication with external simulators and programs).
- *Image/Roman* (product of Carlow Associates): Supports top down mission analysis and provides guidance for allocation of functions and tasks between humans and hardware/software.
- *Envision/ERGO* (product of Delmia Corp [formerly Deneb Associates]): Provides capabilities to physical environments, processes and human operators.
- *Interchange* (product of Trident Systems Incorporated): Provides an advanced object-oriented information repository specifically for engineering projects.
- *COMET* (government off the shelf): Used by the US Navy in estimating personnel costs.

Certain new tools are also being developed under the SC 21 MAI to support human centered design, including:

- Human Centered Design Advisor (HCDA): Provides guidance on implementing and executing the human systems engineering process.
- Team Integrated Design Environment (TIDE): Supports the structuring of command organizations to manage and operate human centric complex systems.

4. SUMMARY

The integrated command environment, as it pertains to warfighting, is one of the most complex control environments in existence today. The functions that must be accomplished by the "commanders" of this environment are many, varied, and often time-critical with life-or-death outcomes. Human performance, in this context, must be optimized. We can select what we believe are "optimum" humans to accomplish this functionality, and we can train them, but no amount of selection and training can compensate for poor design.

Communication and integration are central to successful design development and there are many mechanisms which facilitate across systems design teams. To optimize human performance within any system, it is important that systems designers adequately address human issues early and often in the design and development of that system. Systems engineers must work hand-in-glove with human factors engineers. Standardized, widely accepted processes must be followed. These processes must incorporate human systems issues. The IEEE 1220 Standard for Application and Management of the Systems Engineering Process (1998), is certainly an important first step.

Secondly, systems designers of all disciplines must endeavor to learn to communicate frequently, using well-understood, common terminology and technical terms. Involvement in the professional groups and societies of the designers and specialty engineers with which we interact is an excellent mechanism for understanding the systems design process more fully and becoming more familiar with their terminology. Advanced systems engineering environments which support the full systems engineering process, such as the HCDE, can facilitate communication and integration while reducing design costs and errors by removing the need to translate system design data between disciplines and automatically flagging design changes and notifying the appropriate personnel.

Finally, the human systems engineering process defined here builds on the strong foundation that has been laid by the ergonomics and human factors communities over the past fifty to sixty years. It attempts to fully incorporate human factors processes which have been defined in other works. It is differentiated from more traditional approaches in that it is fully imbedded into the systems engineering process and terminology. Use of a rigorous process such as defined here is critical to enhancing system and human performance, quality, and affordability.

The systems engineering community has realized that humans must be considered as critical systems elements. At a maximum, hardware and software may be designed for the persons using them, from a design's inception to the systems disposal, taking into account human capabilities and limitations in each step of the design process and in each aspect of the system's life cycle.

REFERENCES

1. Kathleen K. Paige, "Human Systems Engineering – A Formula for Success," *Insight*, April 2000.

2. Chief of Naval Operations (N86), RADM M.G. Mullen (Letter Ser N869/9U654332 of 25 May 1999) "Optimized Manning Requirements and Human System Integration."

3. Hamburger, T., *S&T Manning Affordability Program Plan*, 1999.

4. IEEE 1220-1998, Standard for Application and Management of the System Engineering Process, 1998.

5. T.B. Malone, *Ship/System HSI For Affordability and Performance Engineering*. Technical Report, Carlow International Incorporated, 1997.

6. Beevis, D, Bost, J.R., Doring, B., Nordo, E., Papin, J.P, Schuffel, I.H., Streets, D., 1994, Analysis techniques for man-machine system design. NATO Technical Report AC/243 (Panel 8)TR/7, Volume 1, Issue 2

7. A. Chapanis, Human Factors in Systems Engineering (New York: John Wiley & Sons), 1996.

8. A. Chapanis, J.B. Shafer, *Human Factors Methods*. Workshop presented at the 39th Annual Meeting of the Human Factors and Ergonomics Society. 9-13 October, San Diego, California, 1995.