A DESIGN SUPPORT SYSTEM FOR CREW SYSTEM AUTOMATION

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ABSTRACT

Crew system design and automation until today remains largely an unstructured, sometimes an ad hoc process. The penalty, of course, inevitably is time delays and expensive redesign and retrofit based on largely a "band-aiding" process. This paper presents a structured design methodology for automation requirements analysis, specification, prototype design, and product development and describes the design and software implementation of a design support system for crew system automation that incorporates multidisciplinary computer-aided design and engineering procedures, tools, data bases, and models. Future enhancements that impact the effectiveness and efficiency of designs produced using such a computer-aided engineering tool are discussed and contrasted with the labor-intensive manual methods of today.

1. Introduction

Crew system automation design remains largely an unstructured, sometimes ad hoc process. To circumvent a number of design related problems, this paper advocates a formal, systematic method for crew system automation design. The primary purpose of this methodology is to establish a nucleus of tools and data available from the beginning of system design that allow early analysis and comparisons of (re)design alternatives.

The crew system presented here is a multi-media interactive station that is an integral part of the crew system of advanced platforms. Specifically, the station includes the control/display configuration, related communications and presentation media associated with supervisory control of advanced vehicles (Figure 1). While vehicle automation methods such as expert systems and other artificial intelligence techniques hold great potential in providing timely and accurate information, without a consistent methodology for determining what and how to automate, the full impact on overall performance improvement can be severely jeopardized. This would be true despite the specific improvements achieved by individual subsystem automation.

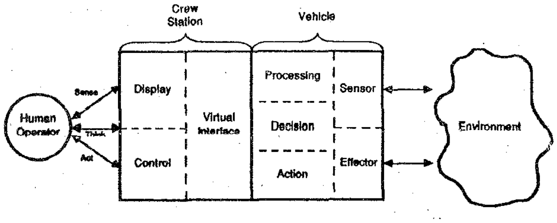

FIGURE 1 THE ROLE OF CREW SYSTEM IN THE SUPERVISORY CONTROL OF ADVANCED VEHICLE

2. The Crew Station Automation Techonology

The term "automation" includes those processes by which essential functions can be performed with partial, intermittent, or no intervention by the crew. Figure 2 presents the primary areas where opportunities for automation exist. Artificial Intelligence (AI) and expert systems technology have reached a level of maturity where it is possible to develop and embed automated systems in future vehicles (Madni and Freedy, 1981; Madni and Chu, 1985; Madni, et al, 1983; Chu, et al, 1982). These studies revealed that automation technology for routine tasks and some pattern matching tasks is now available.

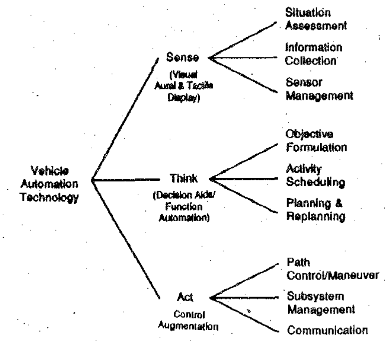

FIGURE 2 VEHICLE AUTOMATION TECHNOLOGY

For example, emphasis in the development of automated systems has been on data and information displays and on sensors -- the "outer" end of vehicle automation. The "inner" part of the problems -- processing these inputs from diverse information sources to improve crew awareness of the outside world and the status of his vehicle -- is just beginning to receive the much needed attention (Madni, 1983).

These earlier studies also noted that full automation can be costly and complex, and may not be necessary at all for all manned systems. Furthermore, there is currently no systematic, widely applied methodology for the design of crew system or vehicle automation. This is a major concern due to the fact that if automation is truly to improve mission performance, vehicle designers must carefully consider where automation would best serve the needs of the crew. They need to examine the technology in light of human strengths and limitations while maintaining cognizance of costs at all times. This requires an understanding of how competent crew members process and assimilate information, and how they conceptualize their tasks, as well as an understanding of the performance characteristics of the controls and displays through which the crew and the automated systems interact (Madni and Moses, 1985).

The lack of appropriate crew system automation design processes has contributed to the design deficiencies and flaws that are not discovered until operational field tests. Attending to the problems at this late stage requires expensive modifications accompanied by sufficient schedule delays. Finally, workload problems are frequently exacerbated with piecemeal automation. The following sections provide a description of a systematic design process, along with prototype design tools for evaluating the different design alternatives.

3. The Crew System Automation Design Process

Crew system automation design decisions are typically made by expert judgement, which means subjective design, rather than research or engineering based design. The goal of the design process presented here is to provide efficient and economical procedures and methods that employ both analytical and empirical techniques for maintaining traceability of crew automation design decisions. The methodology constitutes a formal attempt to systematize the automation design process. The process is designed with the recognition of five key factors that contribute to the efficiency of the process: (1) the completeness and diagnostics of the system performance evaluation process, (2) the soundness of the rationale and the technical rigor behind the function allocation process, (3) the traceability of all assumptions and audit trail behind all design decisions, (4) the evaluation approach devised for comparing alternative automation interface options, and (5) the judicious use of the component technology, and historical lessons learned data bases.

While there have been a number of efforts directed toward a more structured crew system design process (Mostow, 1985; Brown and Chandrasekaran, 1984; Medland, 1985; Duvvuru and Rychener, 1986), the specific application of these design processes turns out to be very complex. The systems do not always have a simple hierarchical structure. Often there are numerous, occasionally hidden interdependencies. Finally, since the design is knowledge intensive requiring the participation of a group of designers, the need for a prototype, test, evaluate and refine cycle is all important in crew system design. Simulations of varying degrees of fidelity are an essential ingredient in the overall design process. Based on these characteristics and the analysis of current crew system design practices, a set of design support process requirements are derived and summarized in Figure 3.

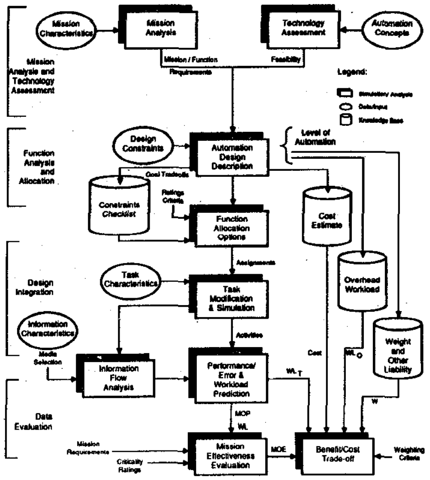

FIGURE 3 DESIGN SUPPORT REQUIREMENTS

4. Crew System Automation Design Support System

Ideally, a design support system should offer the designer the ability to turn a system description/specification into a final design without being concerned with intermediate steps. This requires complete integration of design tools within a highly interactive graphics environment, capable of supporting computational, reasoning and "lessons learned" cataloging functions.

The key premise of the design framework is that crew system designers are able to do their job because they have a fair amount of partially-consolidated knowledge (formal, intuitive, and experimental) of the overall operation of the system. This knowledge provides the basis for their specific conceptualization of the design. As such, expert models can serve as front end to guide the designer through the design phase by sharing its knowledge of when and how to use various computational and reasoning tools. The specific models required for crew system designers include mission analysis, function analysis and allocation, and information flow analysis. Each of these models can be used at the appropriate stage of the design process discussed earlier.

Mission Analysis Model. The purpose of the mission analysis model is to provide proper criteria for successful crew system performance and effectiveness. Our approach is based on the decomposition of mission functional flows coupled with a decision analytic framework for specifying hierarchical mission goal hierarchies.

Decision analysis offers a normative framework for problem-structuring, option evaluation and selection. Specifically, Multi-Attribute Utility (MAU) models are used for characterizing mission goals and tradeoffs among the objectives that characterize the attainment of the goal. However, in of itself the MAU models offers a static framework incapable of responding to events, tasks concurrencies and uncertainties associated with operational tasks. To this end, we combined an active network model with the decision and the MAU model. The active network is a modification of Petri nets called Modified Petri Nets (Madni and Chu, 1985).

A Petri net is an abstract, formal model of information flow. The properties, concepts, and techniques of Petri nets are being developed in a search for natural, simple, and powerful methods for describing and analyzing the flow of information and control in systems, particularly systems that may exhibit asynchronous and concurrent activities. The major use of Petri nets has been the modeling of systems of events in which it is possible for some events to occur concurrently, but there are constraints on their occurrence, precedence, and frequency. Petri nets have been used in the studies of parallel computation, multiprocessing, computer system modeling, and knowledge representation, as well as human expert behavior (Chu and Madni, 1985). Petri nets have been adapted and modified in an attempt to overcome either a specific shortcoming or eliminate certain features that can potentially introduce unwarranted complexity in the computer implementation of the expert crew performance and task execution. These are referred to as Modified Petri Nets (MPNs). The characteristics of the MPN are described in Table 1.

Table 1. MPN Characteristics for Expert Task Analysis

Representation Power
- Decisions
- Events and Associated Uncertainties
- Concurrent and Asynchronous Task/Processes
- Priorities
- Activities (Perceptual, Cognitive, Motor)
- Time Tied to Occurrence of Events
- Variable Precedence Among Events and Activities
- Multiple Levels of Abstraction

Prescriptive Power
- "Executable" Network Software
- Workload Envelopes and Comparisons
- Performance Envelopes

Verifiability
- Against Manned Simulations
- Laboratory Experiments
- Flight Tests

Explanation Power
- Audit Trail Maintained Via Token Propagation Patterns
- Explanations Specifically Tied to Tokens

While the active network generates mission events, task sequences and concurrencies, the decision model evaluates mission performance and overall goal attainment.

Using mission decomposition as a guide, an interactive analysis can be conducted for developing and cataloging representative design scenarios. For each design/mission modification, the affected scenarios are augmented by an appropriate multi-level concurrent processing network. Performance and effectiveness profiles are then computed for each design modification. Clearly, the cumulative impact of individual design modifications are determined by combining the impacts of the multiple consecutive layers of subnets.

For example, the performance computation under this framework can be performed for each selected mission/function segment for each design modification. The predicted impact on performance for each representative task segment can be compared (via appropriate sensitivity analysis) across the mission variations. On the basis of these comparisons, the need for redesign can be assessed.

Function Allocation Models. The function allocation model is at the heart of the crew system automation design process. Given certain advances in automation technology, precision in allocation of functions between crew and machine can produce yet greater force multiplication effects.

Beginning with a clear description of the function to be assigned, the suitability of each function as a candidate for automation is considered in this model. If the function is particularly suited to being performed by a machine, then the issues of time, cost, and risk are addressed. The function is ultimately assigned to a machine if all the criteria are met. If the criteria for any or all of these issues are not met, the function is considered for shared human-machine handling. If this turns out to be the case, then the function is assigned to "machine-aided human." A modification of the system's requirements is only required if the function cannot be performed by the machine alone or by a human-aided machine (Madni, 1983).

If, for some reason, the human cannot match the performance criteria, the designer must re-evaluate the function's description and allocation/partition. Redefinition of functional requirements may be called for if the designer discovers inadequacies within the overall function description. Given a specific function allocation scheme, an interactive analysis can be conducted for assessing the pilot workload and performance based on the execution of the active task network model.

Information Flow Model. The purpose of the information flow analysis is to provide a depiction and analysis of all information flow in a crew system as a function of mission characteristics and design alternatives. The model capabilities include the analysis and depiction of information flow between the crew members and the crew station. Of particular importance is the representation of the critical information items and the "message passing" mechanism used that has high impact on the crew/system performance and effectiveness. The underlying framework used for this model is the object-oriented representation of the information requirements and control/display interface that can be selectively activated by the execution of the task network. The information time and frequency of use can be computed for different function allocation alternatives and crew vehicle interface design.

The MPN models as used here provide a convenient common base for data transfer and design documentation among the three design support models. It forms the basis of an integrated design support framework.

Test/Validation Models. The objectives underlying test/validation are to provide an approach with detailed methods and procedures to determine the demonstration/validation phase of vehicle development if the design specification would indeed satisfy the objectives. The three major criteria for this determination are: compliance, performance, and adequacy.

Since the accuracy and utility of a particular design is directly related to the validity of the data/rules that reside in the earlier design process, it is critical to evaluate the validity of the data/rules provided by the designer in the use of the earlier models. Testing these knowledge/data is, however, an especially difficult task. Testing any data/rule set thoroughly requires a large number of test combinations and iterations.

Furthermore, the nature of most knowledge base requires multiple iterations of the rule/data refinement process. Consequently, we have followed most knowledge-based approaches and adopted an incremental design/testing approach to validating the model/data behind a particular design. Following this approach, we can take advantage of the hierarchical nature of the MPN framework and suggest the use of the following procedure for implementation and testing:

1) Designer-driven data/rules be depicted in a relatively simple model representation.
2) Case experience (e.g., from field operation data logs) be available in the form of stored cases with known performance.
3) Performance data gathered in the implementation stage be compared with data gathered in the previous test stage or lessons learned.

Going through these steps for revising the data/rules usually involves a substantial amount of analyses to determine which data/rules to revise and the specific changes required. The MPN formalism helps designers in this step by providing a layered presentation and by suggesting proper observables for comparison test and evaluation.

5. Design Support Software Prototype

Based on the design models described above, a design support system (DSS) software prototype has been developed for assisting in the mission analysis, function allocation and system integration stages of crew system design. A composite crew mission scenario and automation concepts based on 1995 technology was used as a baseline. The system is implemented on Symbolics 3670 workstation using Zetalisp and Flavor software development environment. The system consists of (1) network representation, execution and evaluation modules, (2) "frame" data, rule set, and world model databases, (3) edit, save, browse, trace, modify, help and explain facilities, (4) menu, window, icon graphics, and (5) computational algorithms pertaining to performance and workload analysis, time and frequency analyses, and graphic mission depiction and evaluation units. Figures 4, 5, and 6 present the multi-window user interface of the DSS. The user interface possesses the following features:

- o Desk-top metaphor
- o Iconic graphics
- o Activity snapshot and Animation
- o Spreading Activation of changes and effect
- o Engineering Design Spreadsheet
- o Data Browsing and modification
- o Direct Manipulation

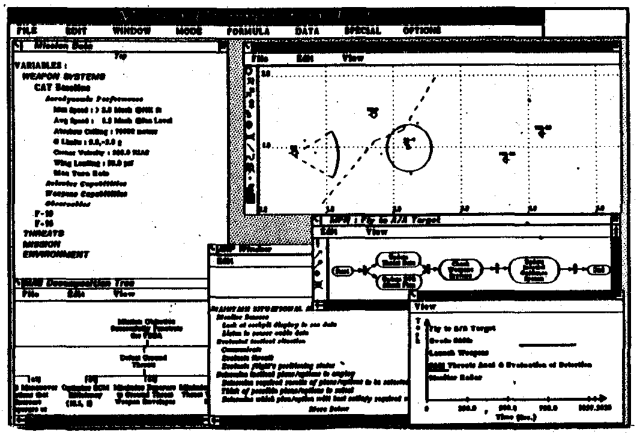

FIGURE 4 MISSION ANALYSIS TOOL SAMPLE SCREEN

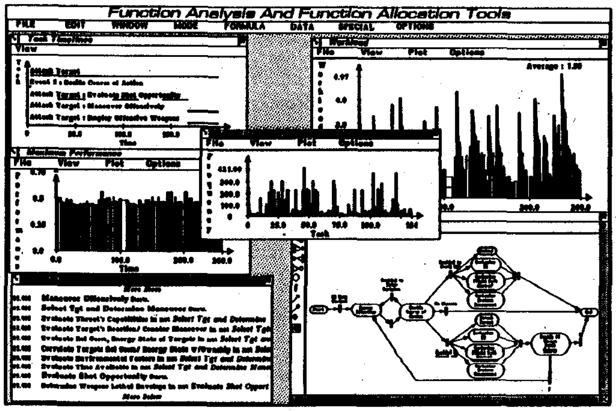

FIGURE 5 FUNCTION ALLOCATION TOOL SAMPLE SCREEN

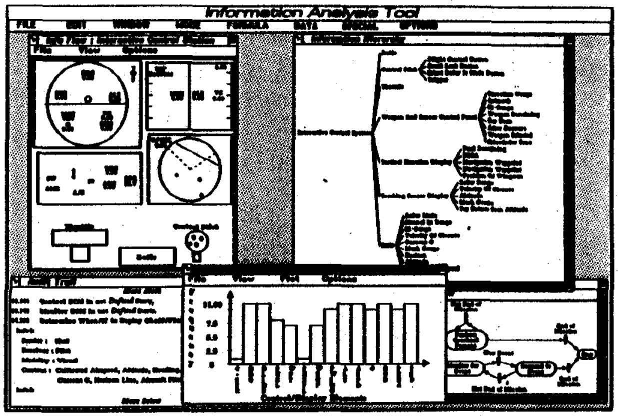

FIGURE 6 INFORMATION ANALYSIS TOOL SAMPLE SCREEN

Conclusion

The major benefits of the design process and design support tools are summarized in Table 2.

Table 2. Major Benefits of the Design Tools

- o Save time-on-task of the designers as well as various subject matter experts (operation analysts, vehicle subsystem effectiveness analysts) and ensure timely recommendations in the system procurement process.
- o Provide systematic comparisons of design alternatives, operation, and training.
- o Minimize the number and magnitude of errors resulting from inadequate front-end analysis.
- o Can serve as a guide for developing performance aids, automation, training, man-machine-interface designs.
- o Can serve as a post-exercise and post flight test reconstruction tool.
- o Flexible framework allows smooth introduction of changes in specification or design.
- o Preserved audit trail for design decisions/ recommendations via "token markings."
- o Allow "what if and why" questions to be posed and answered.
- o Explicit representation lends itself to embedding explanation facilities for justifying recommendations and design changes.

The capability of the expert model-based design methodology and the prototype design support systems to produce a superior crew system design is currently being demonstrated and evaluated in conjunction with a full-mission manned system simulation. Key benefits of the design process, such as reduction in design time or cost of development will be identified as part of this evaluation. A staged development/demonstration of the validity of the design support model is currently underway. A detailed test and validation plan is developed which calls for the comparison of the performance of the "point" design arrived at using the system methodology versus the performance of a baseline system, for the same mission.

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