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SUMMARY

This paper discusses operator role definition and human-system integration from a perspective of systems engineering and allocation of functions. Current and traditional allocation of tasks/functions can no longer be applied to systems that are significantly more sophisticated and dynamic than current system designs. For such advanced and automated designs, explicit attention must be given to the role of the operator in order to facilitate efficient system performance. Furthermore, such systems will include intelligent automated systems which will support the cognitive activities of the operator. If such systems share responsibility and control with the human operator, these computer-based assistants/associates should be viewed as intelligent team members. As such, factors such as trust, intentions, and expectancies, among team members must be considered by the systems designer. Such design considerations are discussed in this paper.

This paper also discusses the area of dynamic allocation of functions, and the need for models of the human operator in support of machine forecast of human performance. The Integrated Reactor Operator/System (INTEROPS) model is discussed as an example of a cognitive model capable of functioning beyond a rule-based behavioral structure.

INTRODUCTION

With the sophisticated technological changes that have been experienced in recent years in the areas of artificial intelligence, microchip development and computational technology, the designers of advanced control systems are experiencing the emergence of a number of new and innovative concepts associated with the control of complex, dynamic processes. These concepts involve such issues as distributed and localized component control, smart sensors, intelligent operator aids, and in general, a trend toward greater levels of automation. The promise of such concepts includes improved levels of reliability, economy and safety. The realization of such promises, however, requires proper implementation of those concepts within a systems engineering perspective, i.e., the objectives and functions of all system elements must be considered conjointly. Such consideration involves the

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human operator as a dynamic system element and requires attention to the role that the operator must fulfill during system operation. While such a premise has always been generally true, it is especially important to keep it in mind during the current evolution of the role of the operator from that of a manual controller, through that of a supervisory controller, to a role of being a high-level manager of system functions. What is evident in this evolving environment is that the traditional approaches of thinking about humans within systems will no longer suffice. Rather, roles for humans and intelligent machines (IMs) must be "designed," just as the function of other critical system elements must be designed. In addition, effort must also be focused to properly integrate such a role within the functioning of a system.

This paper will discuss research that focuses on the emerging roles of operators within complex and dynamic environments. It will present information concerning suggested relationships between human operators and IMs, and characteristics of these relationships. The concept of an intelligent operator associate will also be described. Lastly, this paper will provide an overview of the human-system integration research that is being carried out by the Oak Ridge National Laboratory (ORNL) in support of the U.S. Department of Energy's (DOE) Advanced Controls Program (ACTO).

BACKGROUND

Over the past decade, the rapid introduction of sophisticated innovations in the areas of computing capabilities and artificial intelligence has allowed for a more serious focus on the development of automated systems in which the operators of those systems are considered to be high-level managers of system functions. Evidence of this increased emphasis may be seen in government programs in the US and elsewhere that are focused on accelerated activities associated with automation. Werbos[1], for example, cites three such large, on-going programs: a National Aeronautics and Space Administration program dealing with advanced automation in space missions, a Department of Defense seed program for the encouragement of defense contractors to emphasize automation, and the Japanese "Fifth Generation" program focused on advanced system concepts.

Such rapid progress has led, in some cases, toward a goal of total computerized automation in which human contributions are purposely excluded[2]. While such a goal is currently only viable for relatively simple processes, until such a goal is more readily realizable for more complex dynamic systems, the human element will necessarily remain as a vital system constituent which must be considered explicitly in the design of such systems. While such explicit attention to the design of the role of the human may currently seem intuitively obvious, practical consideration of such concerns are rarely reflected in final system designs. A number of reasons can be conjectured to account for this phenomenon. They include a general lack of knowledge about human performance by system designers, a lack of resources to consider human performance, and failure to recognize the need to consider human performance. In general, however, consideration of human performance has not been a large part of the traditional design process. Only recently, with the increasing interest in systems engineering, has consideration for the design of operator roles been recognized formally as a part of the system design process.

The fact that the traditional design process does not include more explicit consideration of the role of the operator within system design is not entirely surprising. The available tools, e.g., the Fitts list[3] (or variations) were not practically oriented for design purposes. The criteria in the lists were difficult to implement, were generally incompatible with traditional design processes, and offered no means for assessing the impact of the criteria on the design. In addition, many system designs, especially manufacturing systems of more than a decade ago, focused on narrowly defined objectives, and were designed to replace primarily physical human functions. For such systems, an in-depth focus on the allocation of functions may not have been deemed necessary because of the relative inflexibility and narrowness of the span of activity designed into the non-human portions of the system. As such, the non-human portions of such systems can be considered to be a prostheses for the humans within the system, i.e., the machines are mere physical extensions and applications of the capabilities of the human. An example of this is given in a study by Roth, et. al.[4] in which technicians attempted to diagnosis faults in electro-mechanical equipment with the aid of an expert system. They found that when the technicians were assigned relatively passive roles, e.g., to provide information to the expert system, or to follow directives, that the overall performance of the joint system (human and expert system) was degraded. Furthermore, the actual role of such passive operators was to amplify the machine's ability to cope with unanticipated variety in the task environment. Unfortunately, their passivity generally failed to allow them to carry out the responsibilities of their role. Roth points out the irony that increased automation is often justified on grounds of human incompetence, yet in practice, it is often that same person who must now help the machine to cope with disturbances beyond its design range.

Often, the rudimentary allocation of functions that is accomplished within prostheses approaches is one of relegation. That is, functions that cannot be economically automated are relegated to the human. Such allocation strategies employ almost no resources for the consideration of the roles that humans must fulfill in order to achieve efficient system operation. Furthermore, by automating functions that are generally considered to be manual or physical, the human operator is generally left with the responsibility of the more complex cognitive activities. While it can be argued that such a situation allows the operator more "quality" time for the accomplishment of cognitive activities, it can also be argued that by the automation of the manual/physical activities, the explicit and implicit feedback cues that are important for the operator to effectively address the associated cognitive tasks, may not be available. Without these cues, the difficulty of the operator's cognitive tasks are greatly increased. Although the observable (i.e., physical) workload of the operator may appear to have been reduced, the unobservable (i.e., cognitive) workload of the operator is usually greatly increased (for a depiction of changes in human physical and cognitive contribution to work process, with different levels of automation, refer to figure 1 in reference 2). Research by Crossman (cited in reference 5) also supports this phenomenon. In discussing process control automation, he points out that the introduction of automatic control of process variables reduces the amount of routine work to be done by the operator but considerably complicates the decisions he must make. Therefore, although the operator may appear to be required to do less, the likelihood of error for those activities that remain (cognitive tasks) are generally increased (hopefully, however, the impact of these errors will be reduced). For those designs in which insufficient attention is provided to "designing" the role of the humans within the system, automation can tend to starve cognition[6]. Therefore, in order to achieve a well-integrated system design, proper allocation of functions must be achieved within a systems engineering perspective.

Consideration of the problem of proper role definition becomes even more complex when characteristics of intelligence are granted and designed into machines. With such intelligence comes the ability of the machine to assume system responsibilities and control. Proper sharing of responsibility and control (R&C) within a complex and dynamic task environment, by a control team composed of humans and IMs, necessitates that the relationships between the two be properly defined. Two extreme examples for such a relationship are: 1) the IM acts purely as an advisor to the human operator who retains all control functions, and 2) the human operator acts as a consultant to the IM which maintains all control functions (other role relationships are explored later in this paper). With intelligence, machines need not be considered merely a prostheses for the human operator. Rather, IMs can be envisioned to function as partners, associates, or some other supportive team member. Where previously ultimate responsibility resided with the human, IMs offer the opportunity to share both R&C.

If the levels of R&C are allowed to vary with the task environment, further complexity emerges. Research associated with dynamic allocation of functions or tasks has received increased interest in the past few years, especially from the tele-operations and robotics communities. A recent workshop[7] dealing with human-machine symbiotic systems addressed such issues as: "trust" between human operators and IMs, the need for bi-directional conveyance of intent between human operators and IMs, and the need for IMs to have a model of the human operator in order to facilitate expectancies about human operator performance.

Proper role definition for humans within advanced complex systems that include IMs requires attention to allocation of functions, consideration of the distribution of R&C, and knowledge of the characteristics of the control task and IM. The remainder of this paper will focus on these topics.

ALLOCATION OF FUNCTIONS

The first formal prescription for allocation of functions can be traced back to the Fitts list in the early 1950s. In this list, Fitts provided qualitative sets of constructs that were better performed by humans, and better performed by the machines of that time. As mentioned earlier, these lists tended to have minimal impact on system design because in general, they were incompatible with engineering concepts. For example, the original Fitts list indicated that humans appear to surpass present-day machines with respect to the ability to reason inductively, and that present-day machines appear to surpass humans with respect to the ability to reason deductively, including computational ability. While both of these constructs still seem to be valid, neither seems to be directly operational for means to impact the design of systems. Since those early days, progress in the area of allocation of functions continues to be made, however, no formalized and generalizable methodology has emerged. Price, et. al.[8] provided perspectives related to allocation of functions resulting from a survey of man-machine systems literature. The results are presented in Tables 1 and 2. Table 1 (adapted from information in reference 8) provides four allocation of functions perspectives that were arrived at through an examination of past methodologies that failed. Table 2 (also adapted from information in

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Table 1.

Allocation of Functions Perspectives From NUREG/CR-2623*

1. A generalized methodology for allocation of functions decisions is not possible.

2. Allocation decisions are iterative, i.e., they must occur continually throughout the design cycle.

3. Psychomotor and cognitive performance differ and require different analysis techniques.

4. Human and machine performance are not antithetical, i.e., tasks exist for which both humans and machines are well-suited, and for which neither is well-suited.

* adapted from information in reference 8.

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reference 8) provides 11 allocation rules that emerged fromthe literature review. What is evident from this review is that effective allocation of functions remains a relatively qualitative art that requires expert judgement for its proper implementation. The utilization of a systems approach is strongly emphasized and integration of an interdisciplinary team is encouraged. Price also suggests several specific rules for allocating functions. These are presented in Table 3. It is interesting to note that the last method focuses on the allocation of functions for affective and cognitive support. Such support refers to the emotional requirements of humans (a need to know their work is recognized for its value, a need to feel personally secure and to feel that to some degree they are in control), and requirements associated with maintaining an adequate mental model of the system and its conditions. Such concerns over "human resources" may provide the basis for efforts to allocate cognitive functions. Allocation of cognitive functions was almost universally not considered because all such tasks were carried out by humans. With the advent of IMs, attention to the allocation of cognitive functions is essential.

When selection from among a set of allocation strategies is desired, designers may be interested in examining a quantitative method by Meister (cited in reference 9). His method requires the calculation of weighted criteria such as cost, performance, reliability, maintainability, personnel requirements, safety, etc., and weights for each design alternative. Weighted criteria are linearly combined and the results used for allocation strategy selection.

The literature reflects little research in the area of dynamic allocation of functions or tasks. Furthermore, the literature does not provide insights into allocation strategies when the roles of humans and IMs are changeable,

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Table 2.

Allocation of Functions Rules Derived From the Literature Review Associated With NUREG/CR-2623*

1. Allocation is, and should be, considered part of the design process. The allocation decision is embedded in other decisions of design.
2. Allocation is an inventive process. Due to the large number of variables that are operating, the process of allocation is usually a customized process.
3. Allocation can be systematically linked to the regular steps of system design.
4. As much as possible, draw from the experiences of analogous technologies.
5. Consider future technology in current allocation decisions.
6. Consider human optimization in terms of selection and training criteria.
7. Allocation should be performed in cycles consisting of inductive hypothesis and deductive testing.
8. Interaction should be provided between the three primary system design decisions, i.e., the engineering decision (hardware and software decisions), the allocation decision and the human factors decision (the means by which the hardware and software are implemented).
9. Allocation should be part of the iterative design cycle.
10. Tools for cognitive analyses should be developed. These include data collection, control-loop mapping of human-machine transactions, attention to cognitive loading, recognition of the need for cognitive support, assuring shared information between the human and machine includes status and intent information.
11. Assure interdisciplinary communication including design documentation.

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* adapted from information in reference 8.

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i.e., if there is a choice for example, between a control environment consisting of human operators and IMs that are equal partners, or an environment wherein the human provides advice to an IM controller.

In summary, allocation of functions research is being recognized as an essential part of the design process. It has in the past focused primarily on what has been called prostheses applications. Such applications included relatively unintelligent machines, designed to consistently carry out a narrow set of functions. The role of humans in such situations could be considered to be that of a working manager. That is, his/her role involves all cognitive functions, total operational responsibility, and the

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Table 3.

Specific Rules For Allocating Functions*

1. Mandatory allocation: Allocate functions as necessary to fulfill required policies, safety considerations, security concerns, etc.

2. Balance of value: The relative goodness of a human and of the to-be-available machine technology is estimated and used as a set of coordinates in a two dimensional decision space that presents human performance vs. machine performance. Decisions should be made with regard to the location of the point on the matrix (specific details are beyond the scope of this paper).

3. Utilitarian and cost-based allocation: Allocate functions on the basis of practical utility and least cost.

4. Allocation of functions for affective and cognitive support: Consider the needs of the human in terms of self-esteem, self-worth, control, alertness, and requirements for the support of proper mental models.

* adapted from information in reference 8.

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requirement to provide to the machine, needed data and/or other resources in order to ensure efficient operability. Consideration of cognitive resources and the automation of cognitive functions is necessitating new research into the areas of cognitive task analyses, cognitive allocation of functions, and advanced interface design capable of supporting operator functions.

OPERATOR ROLE DEFINITION

Prior to the introduction of artificial intelligence to human-machine systems, operators (at best) were considered to be working managers. That is, the operator was responsible for decision making, trouble shooting and other cognitive functions, while at the same time being responsible for efficient system operation, i.e., providing to relatively unintelligent machines all resources required to maintain functionality. Given such a complex task environment, and (as mentioned earlier) existing biases toward practical application of proper allocation of functions, it is no wonder that we quite routinely hear or read about failures of complex systems. For example, Rouse and Rouse[10] indicate that 70-90% of major accidents in the aircraft, process and power industries have been traced, at least in part, to human error. Other examples involving failures of complex systems that involved human error include the accidents at the Three Mile Island and Chernobyl nuclear power plants. Reason[11] provides an even more gloomy outlook by indicating that serious incidents tend to be novel events and that when the plant experiencing such an incident is returned to a safe state, it is generally due to a mixture of good luck and laborious, resource-limited, knowledge-based processing. Unfortunately, even such overwhelming statistics have done little to overcome failures to recognize the potential impact of poor human performance. For example, when Rouse and Cody[12] questioned why such a large proportion of the problems occurring in complex systems were attributed to the human elements of operating, maintaining and managing these systems, they found that there was a tendency to answer the question with the assertion that people's inadequate abilities and/or poor attitudes were the underlying problems. That is, the responders implied that if people just acted smarter and tried harder, most of the problems would disappear. Such attitudes serve to reinforce the biases that already exist regarding practical implementation of allocation of functions.

Fortunately, technological innovations, and concerns over safety and economics persisted in the support of research in the area of automation in man-machine systems[13]. Technologically driven efforts in the area of automation, however, were also not free from problems. Woods[14] provides four examples of unintended and unforseen negative consequences from purely technology-driven deployment of new tool building capabilities (e.g., decision support tools). They are presented in Table 4. Wood emphasizes that in order to develop effective decision support tools, technologically

Table 4*

Examples of Unintended and Unforseen Negative Consequences
That Have Followed From Purely Technology-Driven Deployment of
New Tool Building Capabilities

- **Cases of shifts from manual to supervisory control in process control where productivity actually fell from previous levels when there was a failure to support the new supervisory control demands;**
- **Cases of automation related disasters in aviation;**
- **A shift in power plant control rooms from tile annunciator alarm systems to computer-based alarm systems. This shift eventually collapsed and forced a return to the older technology because strategies to meet the cognitive demands of fault management (that were implicitly supported by the old representation) were undermined in the new representation;**
- Shifts from paper-based procedures to computerized procedures that have also collapsed due to disorientation problems as a result of a failure to anticipate the cognitive reverberations of technological changes.

* from reference 14.

oriented design approaches need to be balanced with a cognitive description of: 1) the interaction of domain problem solving demands, 2) problem solver characteristics, and 3) characteristics of the available tools.

Recent research in the area of advanced human-system interface design, however, have addressed a number of cognitive issues. For example, research by Eberts[15] addresses the relationship between information displayed to a user and the mental model that results after the interaction. His research points toward the ability to characterize users' mental models through the use of rules generated from experimental data. The development of interfaces that support an operator's mental model could significantly improve the degree of cognitive support to the operator and reduce the potential for operator error. Other research involves such issues as mental workload and adaptive interface design (for example, reference 16). Such cognitively oriented research is of the type needed to investigate the functioning of systems that include human operators and IMs.

As computational technology increases, it offers new machine power that greatly expands the potential to assist and augment human cognitive activities in complex problem-solving worlds[14]. IMs will be capable of supporting human cognitive functions such as trouble shooting, problem formulation and solving, fault management, fault diagnosis, metaphorical reasoning, and perhaps even learning, planning, and inductive reasoning. With such new power on the part of IMs, their span of application is greatly enlarged. Instead of being focused entirely on prostheses functions, IMs will be able to assist, and even take responsibility for various human functions. Such a situation brings to mind a team of human operators attempting to provide control for a process. In the current case, however, one of the team members is not human. Just as relationships between team members composed entirely of humans must have a designated structure, e.g., a leader who makes decisions and followers who implement the decisions, so too must the relationship (structure) between humans and the IM be designated in order to ensure efficient performance. Without explicit attention to these structures, the specific roles of humans and IMs will likely manifest themselves in a fuzzy or ad hoc fashion and will generally be suboptimal with respect to the system performance potential. The analogy between teams composed entirely of humans and teams of humans and IMs can be extended to include specific roles related to different combinations of R&C, communication between the entities that share R&C, as well as characteristics such as "trust" and "intent."

The interaction of two team members in an attempt to produce satisfactory system control requires the proper allocation of responsibilities, the proper allocation of control functions and the appropriate type of communication to link command and control. Command in this case refers to the array of options available to ensure that responsibilities are met. In research focused on operator roles within the dimensions of R&C, Schryver[17] developed the matrix that is reproduced in Figure 1. This 3X3 matrix provides nine operator roles that are the result of various combinations of R&C. It is interesting to note that if two team members jointly share all of the R&C, their roles are those that are physically opposite in the matrix, e.g., the supervisor and the assistant. It should also be noted that as one proceeds from consultant diagonally to sole participant, the degree of engagement in system R&C increases.

For some of the roles in the matrix, specific characteristics can be identified. For example, a "supervisor" role has the characteristics of full responsibility with no control. The assistant, on the other hand, assumes full control without responsibility. The teaming of these two roles can be viewed as an extreme case of a supervisory control structure. That is, a human supervisor can be envisioned to carry out his responsibilities through the computer-based assistant's control abilities. Such an arrangement is susceptible to turning into what was discussed earlier as a prosthesis structure. That is, if the human supervisor acts primarily as a monitor of the assistant, and generally tends to treat his supervisory role in a relatively passive manner (which he may do if he feels removed from direct involvement), the team's overall efficiency will most likely be low. This relationship also requires a high degree of cognitive support for the human operator/supervisor. That is, because the operator has no direct control functions, there is a need for the operator to be kept involved in a meaningful fashion in system functionality in order to maintain alertness and an updated mental model of the system. Systems for which the operator has been taken out of the loop generally fail to provide adequate cognitive support. The inverse role structure of having a computer-based supervisor with a human assistant (i.e., no responsibility and full control) is generally considered to be an inviable option and will not be discussed.

Another team structure in the matrix of Figure 1 involves the senior partner/junior partner combination. This is analogous to a master/apprentice relationship. For such a situation, the master maintains complete responsibility, but has relegated some of the control functions to the apprentice. It is uncommon for existing complex dynamic systems to have a computer-based master with a human apprentice. The sole participant/consultant team may be viewed as a human controller working with an operator aid. That is, all R&C is maintained by the sole participant, and the role of the consultant is to provide advice, interpretation, and assessment. With the introduction of sophisticated operator support systems and management information systems, such relationships are becoming quite common. This relationship however tends to be highly sensitive to human operator acceptance. Newly introduced aids tend to be viewed with skepticism unless: 1) the aids are properly introduced into the operating environment (i.e., not forced on the operator), and 2) the aids fulfill a genuine need on the part of the operator. With the human operator as the sole participant, this relationship may be susceptible to problems associated with high levels of cognitive workload. That is, since all R&C reside with the human operator, requirements for cognitive functioning such as decision making and fault diagnosis may at times be excessive. Therefore, attention must be focused on ensuring that excessive levels of cognitive workload are avoided.

The sole participant/consultant relationship can also be used to envision a totally automated control system in which the human plays the role of an advisor. In such a case, the automated control system will have total R&C, and the human's primary role would be to suggest or advise appropriate control strategies. Such a situation is vulnerable to the need for cognitive support. That is, it may be difficult to maintain proper alertness or to ensure adequate mental models for the human operator in such a relationship. Such a situation is also susceptible to promoting a relatively passive role

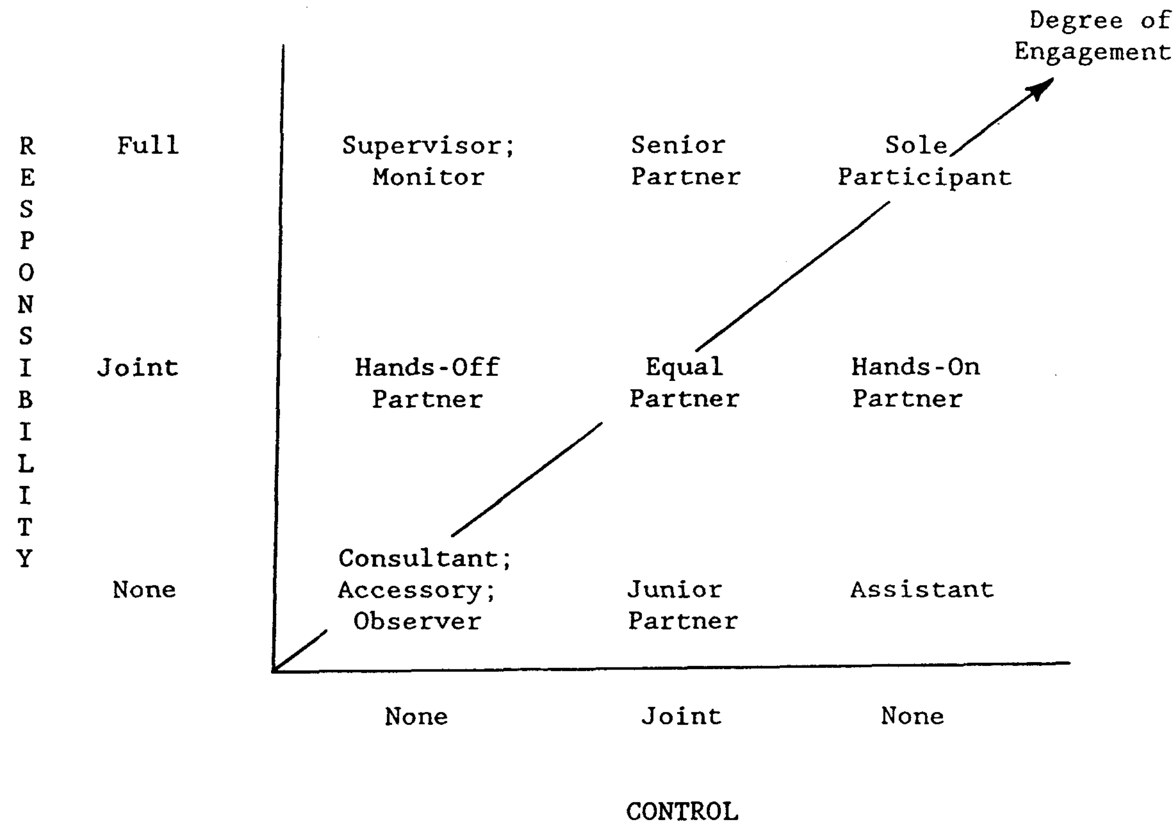

Figure 1. Operator Role Space*

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* from reference 17.

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on the part of the human operator. That is, without formal R&C, it is easy to imagine that the human may view h(is/er) role as having little job enrichment.

The partner roles that are reflective of the middle row of the matrix in Figure 1 offer two interesting relationships that are perhaps more viable with respect to complex dynamic systems. The hands-off/hands-on partner relationship shares responsibility between the two partners and allocates full control to only one of the partners. It is interesting to note that because responsibility is shared, an important type of communication that must take place between the two partners is "explanation." That is, through explanation (and possibly negotiation), a common control intention should be formulated prior to any control action. By sharing responsibility, the partner without the capability for control also has a vested interest in remaining an active participant within the relationship. On the other hand, the hands-off partner is highly susceptible to the need for cognitive support. That is, with joint responsibility and no control, such a role is susceptible to problems of alertness and maintenance of an updated mental model of the system. Such relationship may also be sensitive to the passivity of the hands-on partner. That is, if the hands-on partner tends to be relatively passive with regard to h(is/er) responsibility, or lacks persuasiveness in h(is/er) explanatory communication, the relationship may have a tendency to relapse into the supervisor/assistant relationship. On the other hand, if the hands-on partner is too active with respect to h(is/er) responsibility, and tends to take a strongly dominant role within negotiations related to control intention, the relationship has a tendency to change to the sole participant/consultant relationship.

Perhaps the most stable relationship in Figure 1 comes from that between two equal partners. That is, both share R&C. For such a relationship, an expanded taxonomy of operator roles may be based on shared or allocated R&C. This taxonomy is presented in Figure 2. Shared responsibility implies that both team members are bound to reach agreement in the formation of any control intention. Allocated responsibility, on the other hand, does not require agreement between the team members. However, if one team member formulates an intention that impinges upon the other's responsibility, the former must obtain permission from the latter in order to implement h(is/er) intention. Shared control means that the same control options are available to both team members. On the other hand, allocated control implies that the set of control options is divided into two subsets and each team member is concerned only with h(is/er) assigned subset of control options.

		JOINT RESPONSIBILITY	
		Shared	Allocated
JOINT CONTROL	Shared	Associate	Competitor
	Allocated	Cooperator	Symbiont

Figure 2. Taxonomy of Operator Roles For Equal Partnership

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* from reference 17.

Associate team members (human and IM) work closely together performing the same tasks, i.e., the human operator and IM share the same overall goals (and responsibility), and control the plant together. In addition, each serves as a back-up for the other, and agreement between the two entities must be negotiated before any new intention is implemented. Communication is a very important aspect of this type of relationship. Specifically, both team members must communicate intention, explanation, and information regarding control activities. The more effective the communication structure, the less likely will be the occurrence of unplanned redundant task accomplishment.

On the other extreme of the associate in Figure 2 is the symbiont relationship. For this structure, separate and independent areas of R&C have been allocated to each entity, and team members work separately for a common purpose. Although agreement is not required when responsibility is allocated, each team member must request and grant/deny permission as needed in order to facilitate the common purpose.

If two team members share responsibility but have allocated control, the structure can be viewed as cooperative. That is, each cooperator has separate control functions and together, they coordinate their activities in order to fulfill their joint responsibilities. Because they share common goals, they work cooperatively together in order to ensure that the goals are accomplished. On the other extreme of the cooperator roles are the competitor roles. These roles are relevant when control is shared, but responsibility is allocated. Since both team members may have different goals regarding their area of responsibility, and since agreement between the team members is not required, control actions taken by one team member may not support the responsibilities of the other team member.

From this discussion of operator role definition, it is clear that in order to design advanced systems that perform safely, economically, and reliably, explicit attention must be paid to the role that the human operator plays in system operation. Such attention is required no matter what degree of automation is required. Even when the operator is kept on the job merely in the event that the automation technology fails, or when the automation confronts an unpostulated situation that is outside the range of the technology, attention must be directed toward providing cognitive support and a level of involvement in system functionality that will minimize h(is/er) potential for error when h(e/he) is required to assume some of the control function responsibilities.

OPERATOR ASSOCIATES

Within relationships between human operators and IMs where R&C is shared, one of the important functions that exists between the two is communication. Communications may be of different types and levels. For example, the content of communication may include: description, procedures, information, interpretation, assessment, intention, explanation, knowledge, advice and prediction. The importance of such communication is that it allows "intent" to be conveyed to the other team member. That is, through various communication media, one team member can convey or assess the intentions to/of the other team member. In addressing functions and forms of human-machine communication, Sheridan[18] points out that "communication at the human-machine (human-computer) interface has two principal functions: communication of the human operator's intent ... to the machine, and communication of the machine's state to the human." Furthermore, Sheridan indicates that the receiver of the communication must acknowledge the receipt and understanding of the communication. For intelligent systems that work within a team structure, communication of the intelligent machine's intent to the human operator, and communication of the human operator's state to the IM must also be conveyed. Such communication is required in order to assess possible future control actions.

Furthermore, once each team member becomes familiar with the control "style" of the other, certain expectancies (a mental model) about their control are formed by the other team member. Information that supports this model (i.e., supportive information related to team member's intentions, control actions, etc.) tends to reinforce the mental model (expectancies) and to build or undermine a feeling of trust in the other team member. A recent paper by Muir[19] supports such a position. She indicates that "the more power [autonomy and authority] they [IMs] are given, the greater will be the need for them to effectively communicate the intent of their actions, so that the people who use them can have an appropriate expectation of their responsibility and interact with them effectively."

The concept of trust is critical for team relationships that involve shared responsibility. From the machine's perspective, trust may be considered to be a form of reliability. That is, when activities, intentions, etc., of the human operator match the expectancies that are generated from a model of the human operator held by the IM, reliability (and therefore trust) is enhanced. The degree of reliability (trust) assessed by an IM will provide the basis for its ability to function effectively in uncertain decision environments. That is, when an IM shares decision making responsibilities and control within an uncertain decision environment with a human operator, decisions by the IM will depend on the degree of human reliability perceive by the IM.

The human operator's perspective related to trust in an IM is perhaps even more complex. That is, in the absence of reliability information concerning IM performance, human operators may be skeptical about its performance, or feel threatened (job-wise) about the presence of the machine. Such biases work against the formation of an effective team structure, and are obstacles in the path of generating human trust in IM performance. Muir makes an additional point related to the roles of operators in automated control systems. She states that if the human operators perceive their role as merely serving as a backup for a possibly imperfect IM, further biases and mistrust tend to be generated. Such a perception can come about if operators perceive that they have no real active role in system operation.

A human operator may also suffer from too much trust in IM performance. Such levels of trust stem partially from consistent, reliable performance by the IM within tasks, problems, etc. that the human operator may not fully understand (due to the lack of training, experience, or even the ability to be actively involved in system operation). Such over-trust may support "blind reliance" on the part of the human operator, i.e., acceptance of IM control actions without question of its intent or motives.

The concept of an intelligent decision support system for human operators in complex dynamic systems is not totally theoretical. Boy[20], for example, describes a knowledge-based operator assistant system that provides assistance in decision making related to orbital refueling tasks. Another example is provided by Mitchell[21]. She describes a conceptual design for an operator's assistant or associate which can provide timely advice and reminders, and, at the operator's request, assume responsibility for portions of a supervisory control task. She indicates that "consolidation of decision making into a team comprised of human operators augmented by a computer-based assistant retains the human operator as an essential part of the decision making team, yet gives the operator an assistant to whom tedious tasks can be delegated under normal conditions or who can assume responsibility for lower priority tasks under abnormal, i.e., high workload conditions." Mitchell indicates that one of the primary characteristics of a computer-based assistant is that it remains subordinate to the role of the operator in system operation. This rationale is based on the premise that within complex and dynamic systems, it is impossible to anticipate and plan for all contingencies. Because of this a computer system cannot be allowed to act as the principal or sole "expert" in system control.

Another characteristic of the human operator/computer-based assistant relationship discussed by Mitchell is dynamic task allocation. Such allocation allows the human operator to prioritize system control activities, take advantage of the computer's strengths, and compensate for the computer's weaknesses in the context of the current system state. Dynamic task allocation is necessary because of the interactive nature of the cooperative control team. She states further that dynamic allocation of tasks requires that the human operator build an understanding and trust for the range of activities that the computer-based assistant handles well, and likewise learn to function effectively in unfamiliar situations when the computer fails to recognize the occurrence of a novel event. On the other hand, the computer-based assistant requires a well-defined knowledge structure that represents information about the controlled system and the operator functions, as well as a problem solving structure to build a dynamic representation of operator intentions.

Although the amount of research related to dynamic allocation of tasks is relatively sparse, there seems to be a growing interest in this area. Morris, et.al.[22] provide some insight into the complexity and recent experimental research in this area. The area tends to be complex because of the need to identify means for the dynamic partition, allocation, and transformation of tasks in response to system or operator state changes in order to maximize system performance (Rouse and Rouse, cited in reference 22). It is receiving increased attention because: 1) advances in software and hardware technology have made implementation of the concept more technically feasible, and 2) increased complexity in system designs are such that the ability of humans or machines to deal effectively with such systems is exceeded. In the study by Morris, et. al., an adaptive operator aid was used to assist operators within an aerial search task. Some issues identified at the outset of their work included the following: 1) what should be the role of the adaptive aid in overall system operation? 2) How should the aid interact with the human? 3) Is it possible for the aid to "understand" the human and supply assistance without overt communication from the human? For their experimental design, three aiding conditions were investigated: no aid, manual aid (with operators making the allocation decision), and automatic aid (with allocation decisions based on models of human performance). Results of their research concluded: 1) overall performance was better with the aid available, 2) although overall performance was better with the automatic aid, operators preferred the manual aid with which they felt they had more control. One reason postulated for the second result is that better models of human performance could enhance the automatic allocation process. What is evident from this work is that efforts associated with dynamic allocation of tasks and functions are critical to advances in the development of intelligent, computer-based operator associates.

HUMAN-SYSTEM RESEARCH WITHIN THE ADVANCED CONTROLS PROGRAM AT ORNL

The advanced controls (ACTO) program at ORNL has as one of its primary goals the development of an integrated advanced control system design environment capable of supporting the entire life cycle of a control system design. Such a life cycle spans activities from preliminary and conceptual designs, iterative design phases, and final test and evaluation of the fully elaborated design (including maintenance and provisions for modifications). Program efforts involve the integration of models of plant processes, control systems and the human operator, and involve a design environment containing facilities (e.g., computer-aided-design workstations), methodologies, support staff, software (e.g., predictive models), and databases to allow designers access to advanced technology in control system design. One of the research areas being addressed within ACTO is that of human-system integration. Guidelines for allocation of function are being developed for early phases of the design life cycle. For designs beyond the preliminary and conceptual phases, a more integrated approach for analyzing the human role within the advanced control system is required. ACTO efforts in this area include the development of a cognitive model of human operator functions. The model, entitled INTEROPS[23-25] (Integrated Reactor Operator/System), is dynamically coupled with a thermal-hydraulics model of General Electric's Power Reactor Inherently Safe Module (PRISM) concept[26]. In addition, INTEROPS utilizes rule-based models written in common LISP, augmented by an object-oriented qualitative simulation model of an operator's mental model of the physical plant.

For the test and evaluation phases of control system design, the INTEROPS model is envisioned as one of the tools to be applied to full scale simulations of the final design structure. As such, INTEROPS would be useful in identifying training requirements and the type/scope/depth of associated procedures, and could be used to identify selection criteria for operators. The model could also be used to study characteristics of team performance. Current efforts within ACTO are focused on the development of advanced control system design and allocation of functions guidelines, and the continuing development and evaluation/validation of INTEROPS.

The development of INTEROPS is a significant accomplishment with respect to cognitive modeling. It possess a sophisticated hybrid architecture (knowledge-enhanced network simulation), and is one of the first cognitive models to take a significant step toward the computer-modeling of operator knowledge-based behavior (as in Rasmussen's[27] cognitive taxonomy) in the problem-solving and off-normal planning domains. Through the use of an object-oriented simulation model derived from qualitative differential equations, or confluences, of the plant processes as an explicit knowledge base for the simulated operator, simulations of proposed actions can be carried out to generate a procedure for an event with which the operator is unfamiliar. Because of INTEROPS's ability to qualitatively generate and test potential operator activities with regard to unfamiliar events, it has a significant advantage over rule-based behavior characteristic of many human models[25].

In addition to modeling the mental model of an operator, INTEROPS also models a number of other cognitively-oriented activities. They include: 1) intelligent dynamic monitoring of plant parameters/states, 2) forgetting, 3) evidence chunking, 4) cognitive tunneling, 5) hypothesis testing capabilities, and 6) errors associated with intention formation. Additionally, the model addresses operator functions such as fault diagnosis, normal and emergency planning, and scheduling and execution of tasks.

INTEROPS illustrates the ability to provide a relatively sophisticated means for modeling human cognitive behavior. Although the model is not yet fully developed and has not been validated, development runs of the model indicate a reasonable account of the cognitive performance of the nuclear power plant operator. As such, a model like INTEROPS may be useful in providing an IM with the ability to infer human intentions in an environment wherein tasks and functions may be allocated dynamically. Furthermore, many of the cognitive tasks performed by such a model are necessary for an IM to be part of a team environment in which R&C are shared.

CONCLUSIONS

This paper has presented an overview of allocation of functions and operator role definition. From the information provided, it is clear that increasing complexity and sophistication of new designs for complex and dynamic systems cannot be approached traditionally. That is, the relatively forgiving nature of past designs with respect to the lack of explicit design consideration for the operator's roles no longer exists. Rather, the human operator must be viewed as a dynamic system element whose role can significantly impact requirements for system design. As designs embrace new levels of automation wherein technology provides intelligent support for operator functionality, and R&C no longer reside solely with the human operator, designers must consider the need to address such non-traditional factors as trust, intention, and expectancy.

This paper has also examined the need for models of the human operator and their role in machine expectancies and forecasts of human behavior. Such models, which are a necessity for intelligent operator associates, are required to be relatively reliable (provide good prediction) in order to facilitate adequate IM performance in uncertain task environments. The INTEROPS model, being developed by ORNL within the ACTO program, was discussed as a model of a nuclear power plant operator. INTEROPS takes a step toward cognitive modeling that is less rule-based and more knowledge-based. A model such as this could be utilized to support dynamic allocation of tasks/functions and computer-based expectancy associated with human performance.

It is evident that the area of human-machine interface, especially with respect to proper definition and design of operator roles, is receiving increasing attention and has been the focus of some new research. As evidenced within this paper, however, a great deal of research is still required in order to address identified issues and concerns.

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