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MODELS OF HUMAN OPERATORS: THEIR NEED AND USEFULNESS FOR IMPROVEMENT OF ADVANCED CONTROL SYSTEMS AND CONTROL ROOMS

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ABSTRACT

Models of human behavior and cognition (HB&C) are necessary for understanding the total response of complex systems. Many such models have come available over the past thirty years for various applications. Many potential model users remain skeptical about their practicality, acceptability, and usefulness. Such hesitancy stems in part from disbelief in the ability to model complex cognitive processes, and a belief that relevant human behavior can be adequately accounted for through the use of common-sense heuristics. This paper will highlight several models of HB&C and identify existing and potential applications in attempt to dispel such notions.

I. INTRODUCTION BACKGROUND

Over the past thirty years, the modeling of human behavior, (and more recently) cognition has been experiencing increased interest. This interest stems from the perception human errors are increasingly leading to diminished plant safety, reliability, maintainability and availability (SRM&A). Technological advancements have led to the elimination of many of the prevalent "bad actors" related to SRM&A allowing human errors to surface as one of the principal contributors. Unfortunately, those who facilitated the technological fixes of the past were ill-equipped to address advances that involved dealing with elements of "soft-science".

Many and varied philosophies have emerged related to the minimization of human errors. Hard core automation advocates insist that the best way to eliminate human error is to eliminate the human. Others insist that since human involvement cannot be totally eliminated, the human should function in a supervisory capacity over a semi-automated control system. Still others emphasize that intelligent, high quality operator support systems should be provided in order to minimize cognitive workload resulting in reduced levels of human error. At the other extreme are those who feel that the human should be the principal controller and be allowed to make mistakes in control in order to facilitate learning (and therefore lead to more optimal human-in-the-loop control and reduced human errors), so long as he is watched by a system that ensures avoidance of a progression toward catastrophic events. The variation within these philosophies emphasizes a lack of understanding of the roles (and their constituents) of humans in complex process control.

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The designs of existing nuclear power plant (NPP) control rooms and control systems have in the past been facilitated with little formal attention to the functionality of the human element within the design. The practical design paradigm regarding the human-in-the-loop was that good engineering, coupled with intense training would result in a workable controllable design. Unfortunately, the high number of incidents of human operator error associated with a large percentage of unplanned unscheduled outages, did not support this hypothesis. Within the nuclear community, such inattention stems from a number of factors including: 1) a general lack of formal awareness and attention to technologies that exist regarding man-machine interface, HB&C modeling and human factors associated with complex process control, 2) a general lack of trust in technologies involving "soft-sciences", and 3) a general lack of appreciation of the positive factors that humans contribute to a control environment, e.g., human ingenuity, innovativeness, adaptability and flexibility.

The designers of advanced NPPs are in-part interested in achievement of increased levels of automation that support a minimization of staffing for control. Such minimization is envisioned to result in fewer opportunities for human error, and therefore an increase in plant performance measures such as plant availability, system reliability, system effectiveness, and when relevant, safety. Realization of such a goal however, requires an explicit and detailed analysis of the roles of humans functioning as part of the process. It is no longer acceptable to design for the human element by default. Without proper attention to designing for optimal human performance, enhanced levels of automation could actually result in decreased levels of the aforementioned plant performance measures. A predictive model of human operator performance can allow designers to explicitly and quantitatively study human behavior within their emerging designs. In addition to having relevancy as a design tool, models of HB&C have relevancy in a number of other areas to be discussed later in this paper.

II. OVERVIEW OF SELECTED HUMAN MODELS

Activities associated with the modeling of HB&C are not new and have, over the past thirty years, produced a number of models that are as varied as the applications for which they were developed. These models range from guidelines related to human capabilities (e.g., Fitts Lists[1,2]) through notions involving the human as a specialized system or processor (see Woods and Roth's discussion of the human as a control system, a communication system, a statistical decision maker, an information processor and a symbolic processor[3]), to sophisticated models that emulate a wide range of HB&C through an integration of such notions. This paper will provide overviews of selected models in an attempt to demonstrate that modeling of human behavior is indeed possible and that their usage has relatively widespread applications. It is interesting to note that the nuclear industry has provided the primary stimulus for the development of many of the more recent and sophisticated models of HB&C; these include the Operator Personnel Performance Simulation (OPPS) model, the Maintenance Personnel Performance Simulation (MAPPS) model, the Cognitive Environment Simulation (CES), the Integrated Reactor Operator System (INTEROPS) model, and the Cognitive Simulation Model (COSIMO), all to be discussed later in this section.

A. Rasmussen's Information Processing Operator Model[4]

Rasmussen's information processing operator model is a paper-and-pencil taxonomy that provides a map or schematic of the elements which make up a sensing-planning-implementation paradigm. The model involves the following eight, generally sequential, primary elements: 1) detection of a need for action (activation), 2) observation of information, 3) identification of present system state, 4) interpretation of consequences, 5) evaluation of performance criteria, 6) definition of tasks, 7) formulation of procedures, and 8) execution. Shortcuts within Rasmussen's model are possible depending on the degree to which the operator has internalized a particular scenario stimuli (i.e., the degree to which the human has been trained to provide either an automatic response [skill-based behavior], or can identify an appropriate procedure [rule-based behavior]). Knowledge-based behavior involves a situation that is relatively unfamiliar to the human, and requires creative thinking. This type of behavior is therefore more resource consuming than either skill- or rule-based behavior. During times of high stress (e.g. during an off-normal event in a NPP),humans will have a tendency to want to engage in skill- or rule-based behavior as opposed to knowledge-based behavior in order to minimize stress and conserve resources.

Rasmussen's model provides a good generic framework upon which to build more specific models. For example, detection, observation, or any of the other elements can be modeled at a more detailed level if needed. On the other hand, the model provides no guidance on how to incorporate performance shaping factors (PSFs) such as fatigue, stress, ability degradation, etc., into the model. Furthermore, the model does not reflect feedback from subsequent elements, and is not a temporally-based model. The model's principal usage has been as a steppingstone for more detailed modeling efforts.

B. The Procedure-Oriented Crew Model (PROCRU)

(PROCRU) is a computer-based optimal control model (OCM) developed to analyze flight crew procedures in a landing approach. As with all OCMs, feedback plays an important role in the running of the model. The model portrays the human operator as a rational controller who attempts to optimize system performance within human perceptual, attentional and cognitive limitations. In effect, the human functions as a control or decision element in a closed-loop, man-machine system. The model can address discrete information processing (e.g., event detection), continuous information processing (e.g., state estimation), procedure selection in order to maximize expected gains, discrete and continuous control, and communication among crew members. Decision making errors can occur due to perceptual, procedural, or workload limitations.

A conceptual model for supervisory control of NPPs has been proposed by Baron (developer of PROCRU) and his co-workers. This model: selects goals, utilizes stored mental models as long-term memory, utilizes short-term memory to store temporal information, selects information to be monitored, performs state estimations and predictions utilizing mental models in order to evaluate alternative options for action, contains a discrete event simulator, performs situation assessment using simple pattern recognition or by accessing knowledge in mental models, makes decisions based on expected net gain, selects appropriate procedures or scripts, and executes procedures. All of the actions taken are effected in a timeframe that is concurrent with the NPP process model timeframe.

Although the supervisory control version of this operator model is more complete than its OCM ancestor, it has only begun to address knowledge-intensive activities of the operator, including planning, fault diagnosis, and problem solving. Integration of these models with knowledge-based models would approximate the kind of approach needed to predict behavior of the operator of advanced control systems.

C. The Human Operator Simulator (HOS)

HOS was developed for the US Naval Air Development Center as a human engineering tool for the test and evaluation of physical layout designs and selection of types of displays and controls. It is a computer simulation model, and is therefore somewhat distinct from the previously described models. A computer simulation model attempts to mimic or to represent some aspect of real life[9] and may involve embedded stochastic processes. The model simulates the performance of a goal-oriented and well-trained operator of a complex weapon system. Simulation detail, down to the level of hand reaches, control device manipulations, eye shifts, absorptions of visual information, and internal information processing and decision making can be achieved. The behavior of the simulated operator is assumed to be predominantly in a rule-based domain, and can be viewed as highly procedure-intensive. Furthermore, because of single channel processing limitations, procedures are executed one at a time.

The general model functionality of HOS is as follows: information about current displays and controls are absorbed into a short-term memory and compared to information stored in a long-term memory; quantitative information is inferred from the comparison and used to determine how to accomplish procedural steps; appropriate anatomy movement (head and eyes, hands and arms, and feet) is determined; and times for body movements are defined[10,11]. The activity times are treated deterministically, while the memory process is treated stochastically. Some validation studies have been conducted. They dealt with prediction of human reach, display reading, simultaneous dial monitoring, and tracking, and have shown good correlation between the predictive functionality of HOS and collected data.

D. Early Siegel-Wolf Models[12,13]

The early modeling efforts by Siegel and Wolf involve a large number of simulation models focused on humans operating and maintaining equipment. These models come from what Siegel referred to as the family of task-oriented models. The three primary models within this family were: 1) the 1-2 man model, 2) the intermediate crew size model (4 to 20 men), and 3) the large group model (20 to 100 men). These models were developed for the US Navy, and generated estimates of success probabilities in task and mission performances, task performance times, and a plethora of other factors related to the quality of task and mission performance and the state of the human teams (e.g., most error-prone tasks, amount of productive time, amounts of idle time, stress profiles for job types, etc.). The models required a large amount of input data (e.g., the intermediate crew size model required more than 90 input parameters), however, utilization of default values ensured that the unavailability of certain data did not prohibit the running of the model.

The Siegel-Wolf models are stochastic in their treatment of task completion times and process errors. Furthermore, the models are characterized as being input-output models. That is, they can provide reliable predictions of human performance given a relatively wide range of PSFs and the complex interactions that exist among them, but do not attempt to assure the psychological plausibility of the individual components of the model.

Time stress (the perception of the difference between the time remaining and time necessary to perform a task) occupied a central role in the early Siegel-Wolf models. Task performance tended to be degraded when time stress took on a negative value. The MAPPS model (developed by Oak Ridge National Laboratory [ORNL] and Siegel-Wolf and associates) departed from the traditional notion of having time stress as the major parameter of influence in the model. Within MAPPS, this parameter was ability loading, and will be discussed in more detail later.

E. The Operator Personnel Performance Simulation (OPPS) Model[14]

The OPPS model was developed by ORNL and General Physics Corp. to predict a probability distribution of time to correctly complete NPP safety related operator actions. It is a relatively simple model of a human operator that utilized characteristics related to task requirements, information presentation and system dynamics to generate estimates of task timing. Cognitive processes were modeled at a relatively gross level. They involved detection of disturbances, internal processing of information, the facilitation of switch manipulations to operate equipment and control the nuclear process, and error recovery in the event of a detected error. The OPPS model characterized errors and some PSFs stochastically. The sources of data to support the stochastic processing came from experiments conducted in NPP training simulators. OPPS was written in the SAINT (Systems Analysis of Integrated Networks of Tasks)[15] network simulation language which is very amenable to the building of human-machine models

F. The Maintenance Personnel Performance Simulation (MAPPS) Model[16]

The MAPPS model was developed by ORNL and Applied Psychological Services for the Nuclear Regulatory Commission (NRC) as a tool for generating human error probability data related to NPP maintenance for use in probabilistic risk assessment (PRA) studies. MAPPS is a Siegel-Wolf type model that focuses on abilities, rather than time stress as a principal model parameter. The notion of utilizing abilities as the focus of the model involves the assumption that ability requirements for successful subtask completion varied with the nature of the subtask and various job factors such as accessibility to the equipment, the need for protective clothing and the availability of procedures. Furthermore, maintenance teams have available both cognitive and psycho-motor abilities that are assumed to degrade with fatigue and other factors such as stress. At any point in time, the probability of successful task accomplishment is a function of the difference between the current ability levels of the maintainers and the required ability levels of the subtask. The model includes a library of 28 generic NPP maintenance subtasks (e.g., activate, connect, inspect, remove) which are utilized within a task analysis to characterize the maintenance task. Furthermore, information from job analyses conducted for four generic maintainer types (supervisor, electrician, instrumentation and control technician and mechanic) provided ability requirements associated with each library subtask.

MAPPS can simulate a crew of maintainers (2 to 8 persons) and addresses primarily activities that are human motor-oriented. The model does, however address decision making and trouble-shooting which tend to be more cognitively-oriented, but does so generally in the input-output fashion that is characteristic of Siegel-Wolf models. The model generates a large amount of output information that is useful for PRAs as well as maintenance structure design and evaluation. It was extensively documented and was evaluated over a years period of time with relatively positive outcomes[17].

G. The Integrated Reactor Operator System (INTEROPS) Model[18,19]

The INTEROPS model is a cognitive model of human functions associated with (required for) the operation of one of three General Electric (GE) modular PRISM (Power Reactor Inherently Safe Module) liquid metals reactors as represented by GE's ARIES-P thermal-hydraulics code. The INTEROPS model is dynamically linked to ARIES-P so that plant state information affects the model of human operator functionality, and the resultant human performance affects the progression of the thermal-hydraulics code. INTEROPS can also be run in an open-loop mode wherein the model provides information related to activities which might be expected to be experienced, but does not actually implement the control activities in the ARIES-P code.

The development of INTEROPS is being conducted within a Department of Energy sponsored program at ORNL entitled the Advanced Controls Program[20]. INTEROPS is a knowledge-enhanced network simulation model programmed within the SAINT network simulation language. It is dubbed knowledge-enhanced because the simulation network has been augmented by a knowledge-base consisting of procedural information required for addressing a selected number of off-normal events. The model is predictive, and can provide information related to the expected cognitive behavior of human operators in the control of a PRISM module.

The human functions modeled within INTEROPS include monitoring, surveillance, attention allocation, classification, interpretation, system failure detection, fault diagnosis, normal and emergency planning, situation assessment and detection of human errors. These models are firmly based on the associated literature. In addition to modeling functions required for control of a PRISM module, INTEROPS was developed to reflect a number of human heuristics and biases. At the current time, five of these have been programmed into INTEROPS. First, the model reflects the human forgetting process, i.e., the importance of a piece of data that the operator has monitored diminishes with time. Second, the model embodies a susceptibility to recency biases, i.e., in performing diagnoses, the operator has a tendency to utilize data and information that is most recent. A third bias involves confirmation bias, i.e., in the process of confirming a hypothesis, a human operator has a tendency to seek data and information that confirms the candidate hypothesis. Fourth, human operators have a tendency to "chunk" data and information, i.e., once the operator engages in a particular line of reasoning, such reasoning will continue until a minimum sufficient amount of evidence has been received that suggests a change to another line of reasoning. Lastly, humans are susceptible to cognitive tunneling, i.e., under high levels of stress, the human operator will focus only on a subset of data and information that is readily available.

INTEROPS is capable of generating a number of output parameters. At the current time, with an emphasis on allocation of function, INTEROPS generates three primary output measures. The first is called cognitive resource utilization and reflects the number of simultaneous cognitive processes being engaged in by the human operator at any point in time. The second measure is called the monitoring task que length and reflects the number of items that require the operator's attention to monitoring. The third measure is time-stress.

The model's primary intent was to be a decision support tool for control system and control room designers. More specifically, INTEROPS's primary function was to provide information useful for allocation of function. Its usefulness, however, goes far beyond its initial intent. It can also provide information relevant to staffing decisions in the control room, assessment of the cognitive loading of the operators, control and display design, determining the content and quality of procedures and the identification of requirements for operator aiding.

It should be noted that although INTEROPS is a network simulation model, it is not an input-output model in the sense of traditional Siegel-Wolf models. What INTEROPS attempts to model are the cognitive activities which when studied, provide insight into how humans function as problem-solvers. Therefore, the human is not treated as a "black box" or a "single-point".

Future INTEROPS research directions include: 1) modeling multi-operator performance, 2) modeling multi-modular control, and 3) modeling of knowledge-based behavior (i.e., behavior which requires creative problem-solving, e.g., in addressing severely off-normal events for which procedures do not exist).

H. The Cognitive Environment Simulation (CES)[21]

The CES was developed by Westinghouse Electric Corporation under sponsorship of the NRC. It is a simulation of cognitive processes that allows exploration of plausible human responses in different emergency situations. CES focuses on the following cognitive competencies: control of attention (including data-driven control of attention, competition for limited resources and evidence processing), situation assessment (involving expectations and qualitative reasoning), explanation building, response management and knowledge representation.

The CES utilizes the EAGOL artificial intelligence problem-solving system[22] (a proprietary product of Seer Systems) for providing capabilities for reasoning in dynamic situations. Because CES models the processes by which intentions to act are formed, it can be used to find points in the cognitive processing which are prone to errors associated with intention formation, and to identify the sources of cognitive processing breakdowns and intention formation failures. CES also provides an analytic tool for investigating the effects of changes in NPP person-machine systems including new instrumentation, computer-based displays, operator decision aids, procedure changes, training, and multi-person problem solving styles.

The CES can function in two modes. First, it can take data and information from a NPP training simulator (or other source of process system data) and can generate control intentions. Although CES does not directly interface with the training simulator, a human subject has been utilized as an intermediary between the CES and the simulator. The second mode involves the CES generating control intentions for a data file of process parameters on an a-posteriori basis. For this mode, there is no control feedback into the process.

The CES has been exercised on several NPP accident scenarios. One case involved a failure in a portion of the system that connected the reactor coolant system to the residual heat removal system[23]. This event was diagnostically challenging because it produced symptoms in multiple regions of the plant that are normally unconnected, suggesting the possibility of multiple independent events. The performance of the CES on this event was successful in revealing the knowledge and reasoning required to diagnose this class of incidents, but it did not account for the difficulty that humans have in assessing the relevant knowledge and integrating the evidence. Future areas of research will investigate the addition of human cognitive processing biases.

A cognitive reliability assessment technique (CREATE) was developed that utilizes the CES to generate input for human reliability analyses portions of a PRA[24]. Within the CREATE technique, CES is run on multiple variants of accident sequences of interest. The variants are selected to provide cognitively challenging situations. The goal is to identify sets of conditions (characteristics of the situation and/or the operator) that combine to produce intention failures with significant risk consequences. Once the range of plausible intention errors and the conditions under which they will arise are identified, a quantification procedure is used to assess the likelihood of these intention errors.

I. The Cognitive Simulation Model (COSIMO)[25,26]

The COSIMO is being developed by the Commission of the European Communities' Joint Research Centre in Ispra, Italy. It involves two cognitive levels of reasoning and decision making. These are: 1) high-level decision making (HLDM) involving exploitation of an operator's knowledge by continuously engaging in situation assessment and by building supervisory and control strategies (planning), and 2) low-level decision making (LLDM) involving a working memory and conscious memory dynamics.

The HMDL includes a knowledge-base involving knowledge-frames (descriptions of the processes and structure of the system) and action-frames (pre-defined plans of action for different situations). The mechanism for bringing the products of the stored knowledge-base into working memory involves "similarity-matching" and "frequency gambling". This mechanism is justified on the grounds that humans tend to engage strongly in pattern matching activities when confronted by a new situation. Within this mechanism, fuzzy set theory is employed along with confirmation bias principals. Planning within the HMDL is assumed to be an analogical process involving selection from amongst the most appropriate action-frames.

The LLDM involves implementation of an identified plan and is accomplished via a Fuzzy-Goal-Oriented-Script (FUGOS). The FUGOS involves a hierarchial goal-oriented structure which decomposes goals into subgoals, and subgoals into acts (portions of tasks). Through a prioritization of goals, and traveling top-down in the FUGOS, acts can be selected for implementation and therefore tasks can be carried out. A blackboard architecture has been proposed as the primary means for implementing COSIMO.

The development applications for COSIMO are various and numerous. At a high level, it is intended to support enhancement of safety by providing means for the design and validation of emergency procedures; the study of the usefulness and need for automation; the evaluation of the completeness and functionality of human-system interfaces and decision support systms; and the design of architectures that support appropriate allocation of functions.

III. APPLICATIONS OF HUMAN BEHAVIORAL MODELS

In reviewing the models that have been discussed in this paper there have been two primary areas of focus for their development. First, there is the area of design. Many of the models described were developed to understand the role of humans in human-in-the-loop process control. These include decisions related to staffing, automation, allocation of functions between humans and automated systems, man-machine interface design, procedure development and assessment, and overall system optimality. The second area involves risk assessment. It is clear that the general unavailability of human performance data makes the generation of such data via modeling an attractive approach.

In general, a number of uses of human behavioral models can be identified. These uses are provided in the following non-exhaustive list:

Reliability/Risk/Safety Assessment Area

- Estimation of human reliability in existing and proposed process control environments.
- Identification of error-likely situations.

- Estimation of improvements in human reliability due to modifications in equipment, procedures, training, etc.
- Identification and estimation of the effects of critical human variables.

System Design Evaluation

- Estimation of the overall effectiveness of system designs.
- Identification of potential human-in-the-loop problems in existing and proposed process control environments.
- Integration of human engineering and personnel-equipment designs into process control enivronments.
- Identification of personnel requirements.
- Development and evaluation of procedures.

Operations Analysis

- Optimization/comparison of control strategies.
- Optimization of the roles of humans.
- Planning/scheduling of operations.

Human Performance Data Base

- Contribution of human performance data and information to a human performance data base.

Other applications of human behavioral models that can be envisioned to be appropriate for future advanced control systems and control room designs. They involve the following: 1) a faster-than-real-time forecasting tool that accounts for uncertainties associated with human activities and actions, 2) as a model of expected human behavior against which actual human behavior could be compared (large differences indicate error-likely situations, and could theoretically be utilized in much the same modality as model-based control), 3) a real-time simulated partner to facilitate team training, 4) an advanced, intelligent, interactive operator associate, and 5) the basis for expectancy models of intelligent machines.

IV. CONCLUSIONS

Models of HB&C have relatively wide applicability. In the design of new and advanced process control environments, models of HB&C are almost mandatory in order to ensure that a philosophy of human-centered automation can be achieved, and that the design facilitates not only a "physical fit" for the human, but a "cognitive fit" as well.

As such models become more widely accepted, and as such models move out of the research environments into the process control industries, it is felt that they will play major roles in elements of system design and optimization.

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