Modeling Control Room Crews in Accident Sequence Analysis

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ABSTRACT

Studies of small groups in business, political, and civil aviation environments have found that communication and other group interactions can be critical factors in evaluating group performance. This paper presents a simulation–based model for a nuclear power plant control room crew that treats these interactions as well as operator cognitive behavior. It also provides a rationale for emphasizing the treatment of group interaction, and discusses the current status of the model.

1 INTRODUCTION

As shown by past operational experience (e.g., the TMI and Chernobyl accidents), operator performance in accident sequences is a critical factor to nuclear power plant safety. Current probabilistic risk assessment (PRA) studies also show the importance of operator actions, but do not explicitly treat a number of issues that may significantly impact the degree of dependence between failure events in an accident. Three key issues are: a) the dynamic interaction between the crew and the plant, b) the dynamic interaction between crew members, and c) the cognitive behavior of the crew [1].

Current PRA studies generally treat operating crew behavior only in terms of successful or unsuccessful performance of specified actions (or related sets of actions). This means that the variability (e.g., in terms of timing, event order) in operator performance of the subtasks underlying each action is not treated. Because this variability could lead to variations in the dynamic plant response, it can affect the likelihood of success for subsequent operator actions (the operator actions being keyed to the plant behavior through training and procedures). Thus, improved treatment of the plant/crew interaction over the course of the accident could lead to a better treatment of the dependencies between multiple failure events.

Regarding the issue of dynamic crew behavior, studies on commercial aircraft crews [2] and on nuclear power plant control room crews [3] identify the importance of group behavior. For example, Ref. 2 points out that many civil aviation accidents have involved breakdowns in crew coordination rather than deficiencies in operator knowledge and skills. Clearly, the characteristic time scale for aviation accidents is shorter than that for power plant accidents; however, in the latter case, crew interactions can still affect the dynamic response of the crew to an accident.

Operator cognitive behavior is another key factor in the assessment of dependencies between events in an accident sequence. Neglect of this behavior means that faults in the operators' reasoning, which could persist for some time, are also neglected. As a

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result, potentially significant dependencies between multiple failure events could be neglected.

Current work addressing these issues concentrates on the first and last problems. In the area of dynamic accident sequence modeling, for example, Ref. 4 describes a limited dynamic event tree analysis in which the operator crew response (treated as a single entity) is explicitly integrated into the model using a number of predefined "operator states." In the area of cognitive modeling, Refs. 5–8 describe a number of models developed to treat operator behavior. These models treat four cognitive activity stages: monitoring, situation assessment, planning, and response management. The models are purely individual-oriented (either they treat the entire crew as a single individual, or they simply treat individuals) and do not consider the interactions among operators and their impacts on individual behavior.

This paper describes a dynamic simulation model intended to address all three issues identified above. This model consists of two submodels: the plant model (treating the plant thermal hydraulics and hardware) and the crew model, which responds to and interacts with the plant model. The crew model itself is divided into modules representing the individual operators. The current version of this model treats informational interactions between crew members; later work is expected to include a limited treatment of emotional interactions as well. The operator modules are used to model the cognitive behavior of each operator. In this simulation approach, group cognitive behavior (e.g., group decision making) is treated implicitly as the result of coupling the cognitive behavior of each operator via communications.

Development of the plant model is conceptually straightforward. The following sections discuss the crew model and the operator modules in more detail, and outlines the current approach for operationalizing these models in a computer code.

2 CREW MODEL

The operating crew model, shown linked to the plant model in Figure 1, is based on a systems approach to modeling. Each module in the model is characterized by its input, its output, and the processing function that transform the input into output. The input/output links between modules are few in number and tightly defined. The approach expands on that used in a submarine crew model described in Ref. 9.

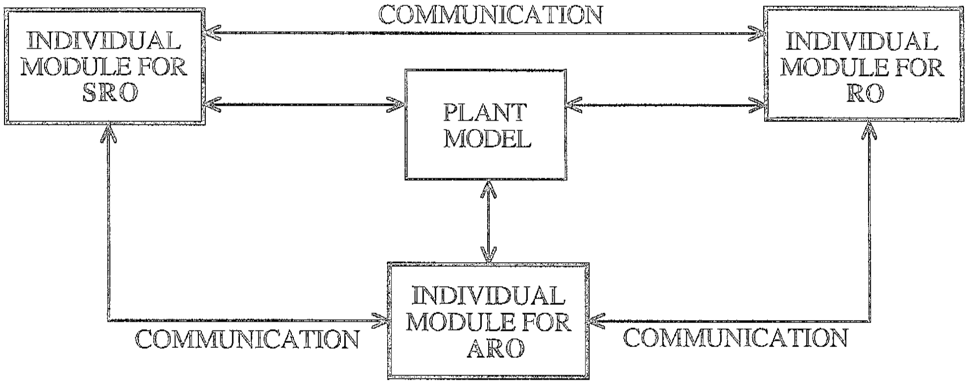

Figure 1. Crew Model

In our primarily cognition–based crew model, the links between the modules carry information. The plant model provides information regarding the status of the plant to the different operator modules; the operator modules send information to each other via communication. The operator modules also send signals back to the plant model in the form of executed actions (these affect the plant hardware state).

Three important features of this model intended to treat potentially significant issues in crew performance are: a) the indivual operators have a limited scope of attention (they cannot observe all plant symptoms), b) the operators have defined areas of responsibility, and c) the communication of information can be imperfect. The first feature is implemented by the use of a "filter function" in each individual operator module. Each operator's filter function is allowed to vary dynamically during the course of the accident. For example, as an operator's workload increases, his/her field of attention narrows; this is represented by modifying the filter function to screen out increasing amounts of less important information from the plant.

The last feature is also implemented using a filter function. In this case, the filtering is affected by the current group structure of the crew. Here, the group structure is represented by dynamic "relative confidence levels" between operators, where the relative confidence level represents the receiver's current confidence (both technical and emotional) in the sender. This confidence level reflects the results of two complex group processes: "influencing" and "coordination" [10]. In the case of communication, it quantifies the degree to which the receiver will accept the message and act upon it, i.e., it is used by a receiving module to modify the importance of a sent message. Note that the matrix of relative confidence levels between operators need not be symmetric.

The relative confidence level is not the only parameter affecting the effectiveness of communication. Allowances are also made for the inherent importance of the message (e.g., whether it is a command or a suggestion), and for some decision-making on the part of the sender (whether or not to send a needed message based on the current group structure, the workload of the intended receiver, the sender's understanding of the receiver's state of knowledge relative to the message, etc.). Note that one form of communication inefficiency, message garbling, will only be treated via the filtering notion; general message distortion will not be modeled in the current work.

The middle feature, the defined areas of responsibility for the operators, are treated by providing tailored knowledge bases (largely in the form of scripts) for each operator module. This is further described in the next section.

As shown in Figure 1, the current implementation of the crew model is fairly limited. It treats a PWR control room crew consisting of three operators: the senior reactor operator (SRO) in charge of the unit operation, the reactor operator (RO) in charge of critical systems, and the auxiliary reactor operator (ARO). It is assumed that the SRO is the lone, formal decision maker, although he may adopt suggestions from the other crew members; "group decision making" is not treated in a general way. This also means that the large number of people who could eventually participate in a real accident response are not treated. (These people include the equipment operators in the plant, experts in the technical support center, additional personnel in the control room, etc.) However, the modular nature of this crew model enables, in principle, a straightforward extension to cover this situation, as well as the problem of different crew compositions for different plants.

3 OPERATOR MODULES

The individual operator modules constituting the crew model incorporate the cognitive behavior modeling necessary to treat the underlying reasons for operator errors. The general structure of the approach described in this section is based largely on previous cognitive models (especially Ref. 5); the primary differences in structure are: a) the approach treats communication between operators, as discussed previously, and b) the approach assumes that much of the operator behavior is scripted.

The second point means that the operators are assumed to follow pre–established programs of action, i.e., "scripts," in response to certain cues. The scripts are the products of individual knowledge and experience in operations, training, operational policies, and applicable written procedures. This assumption correponds with observations of operating crews performing training exercises for accident response [14]. It allows the treatment of the automatic, trained responses of operators to changes in plant condition, an important factor when modeling the highly structured, procedure-oriented behavior of crews in current power plants. It is also useful in two other ways. First, it allows treatment of linked groups of actions. This in turn allows a relatively simple treatment of "confirmation bias," where an operator picks a wrong script and follows that script despite mounting evidence that the script is incorrect [5–8]. Second, using different scripts for different crew members can be used to model situations where the crew members are on "different pages," leading to poor team performance. Note that these issues are more difficult to handle in models which treat operator rule–based behavior as chains of independent decisions and actions.

Of course, it cannot be expected that an operator will have a script (correct or incorrect) for every possible circumstance. In such situations, the operator may resort to more detailed reasoning. (Given the current workload/stress environment, such a transition may not be possible, since this places a greater cognitive workload on the operators than rule–based behavior, which employs pattern matching extensively.) This model allows for the possibility of a transition to knowledge–based behavior, as described later in this section.

Figure 2 shows the elements of the module used to represent an operator in this work. The upper elements largely represent routines used to process incoming data for the purpose of identifying an appropriate script. Execution of these routines is assumed to occur in a negligible amount of simulated time. Two of the lower elements represent the operator's knowledge base; short term memory and long–term memory are distinguished. The other lower element represents a control activity process (which can take a finite amount of simulated time to complete); this process is created and started when there is a demand for logical reasoning. Not shown are the process elements associated with the actual execution of tasks. Not all of the elements in Figure 2 have a strong one–to–one relationship with actual psychological processes; they are used to generate a simulation model with the desired behavior.

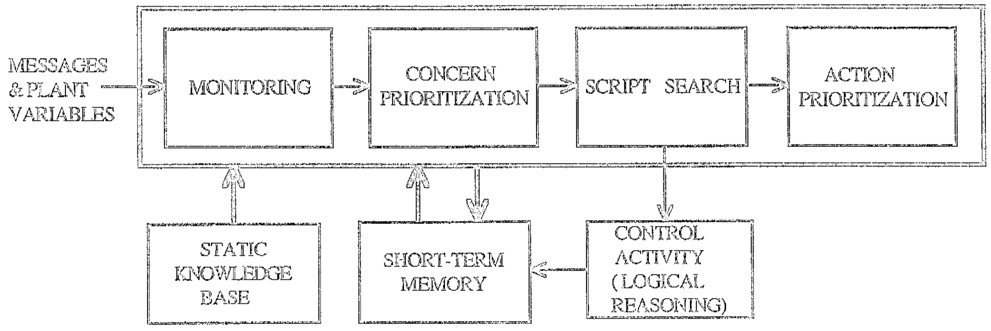

Figure 2. Individual Module

Walking through the model from left to right, it can be seen that incoming information (either plant parameters or a message from another operator) enters a monitoring routine. This routine is used to filter out information that does not have a sufficiently high "importance value;" the filter threshold, as discussed previously, can vary dynamically depending on the state of the operator and the current group structure.

The next routine is used to model the fact that the operator can only start on working on one new problem at a time (although there may be a number of existing issues being worked on in parallel). The routine provides a prioritization of the different "concerns" currently recognized by the operator, i.e., it performs a situation assessment function. To determine if the received signal is a concern, the routine checks with the short–term memory data base to decide if the signal is expected. If not, a concern is defined, assigned an importance, and filed in a list of concerns (the "concern queue") prioritized by "importance."

The "Script Search" routine is used to identify a script (contained in the static knowledge base) for the top concern in the concern queue. The script usually contains both a set of mitigative actions and a call to initiate a fault diagnosis process. For example, when the concern is "pressurizer level decreasing," the script may require a message transmission (notifying the other operators), actions to start equipment, and fault diagnosis to find out why the level is decreasing. The found script is then passed to the next routine ("Action Prioritization"). If a script is not found by this routine, a "control activity" involving logical reasoning will be initiated.

The control activitity process is used to model knowledge–based behavior. Its two major functions are to generate procedures not covered by the stored scripts and to diagnose faults. As in the case with other processes (namely, the action execution processes), the control activity is performed over a finite amount of time, and is therefore executed in parallel with all other processes.

The last element in the upper row of Figure 2 is used to prioritize the different actions planned by the operator. The planned actions are filed in an "action queue" (also prioritized by importance). Note that the distinction between the concern queue and the action queue allows separate treatment of problems to be addressed and actions to be performed. Note also that the use of queues allows the identification of situations where the operator workload is increasing; by limiting the size of the queues, situations where there are too many concerns/actions to process can also be modeled.

The routines and processes described above rely on two data bases. The static knowledge base contains scripts and initial values of the operating crew group characteristics. After the accident sequence begins, continuously updated variables are stored in the short–term memory. Also stored are a large variety of information that can affect crew performance, including: the current (dynamic) plant status observed by the operator, his/her understanding of the other operators' knowledge about the plant, the expected current status of systems/components, etc.

4 MODEL IMPLEMENTATION

The crew simulation model is being implemented using SIMSCRIPT II.5 [12], a discrete event simulation language that treats parallel, random processes. (The notion of a script very closely parallels the notion of "processes" used by the simulation community.) SIMSCRIPT II.5 also allows: the creation and use of the nested data structures needed to represent an operator's short–term memory and static knowledge base, and the creation of a modular model, an important point when considering the expansion of the model to accommodate additional operating crew members.

The model is aimed at the analysis of the steam generator tube rupture accident. This scenario can be relatively complicated, and can require a good deal of operator actions. Further, the scenario has been observed in real reactors and is the basis for numerous training exercises. Therefore, information on crew behavior during real or simulated accident is available; this information is being used in creating the model.

5 CONCLUDING REMARKS

The crew model described in this paper treats each of the control room operators as a separate entity whose behavior is usually script–oriented, but can involve control activities. Group interactions are modeled via communication and individual processing of the communication. This model is aimed at filling the gap left by currently used models, which account for observable human errors, and more recent individual cognitive models, which account for underlying reasons for these errors.

Currently, the emphasis of the work is on the cognitive aspects of crew behavior (i.e., the processing of information directly relevant to the accident). This emphasis is due to the direct effect the cognitive behavior has on the evolution of an accident sequence. However, emotional factors can clearly affect the cognitive behavior. Work on better defining these factors and their interaction with the cognitive model is ongoing.

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