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Dynamic simulation of knowledge based reasoning of nuclear power plant operator in accident conditions: Modeling and simulation foundations

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ABSTRACT

This paper describes major additions to the modeling and simulation capabilities of the Accident Dynamic Simulator paired with the Information, Decision, and Action in a Crew context (ADS-IDAC), a platform for conducting dynamic probabilistic risk assessment (DPRA) of nuclear power plants. The new advancements are mostly in modeling of operator knowledge-based behavior in accident conditions, enhancing realism of the IDAC model, and simulation approach to Human Reliability Analysis (HRA). The focus is situation assessment and diagnosis of the accident cause. Knowledge-based reasoning plays an important role in this phase. A reasoning module has been developed and implemented in ADS-IDAC to simulate operators' knowledge-based reasoning. This paper describes the cognitive architecture of the reasoning module, including knowledge representation (model of operator's understanding of the plant systems and functions), a memory representation, information processing flow, reasoning sequence generation, and rules for accident diagnosis. Some theoretical and empirical insights for human error prediction are embedded in this causal model as simulation rules. Human cognitive limitations and heuristics that potentially contribute to human errors are explicitly modeled. Together with the model description, several example simulations are provided to demonstrate different features of the reasoning module. Examples of the simulation show that the reasoning module in ADS-IDAC produces realistic knowledge-based responses by capturing cognitive limitations, deliberative reasoning, and dynamic of accident progression.

1. Introduction

The Accident Dynamics Simulator paired with the Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC) is a Dynamic Probabilistic Risk Analysis (DPRA) software platform that probabilistically simulates the response of a nuclear power plant and its control room crew to a postulated accident. Among other features, it aims to identify potential control room operator errors in accident situations, particularly errors of commission.

This is the one of three papers describing major additions to modeling and simulation capabilities of the ADS-IDAC platform (ADS 3.0). This paper introduces the models and key algorithms of operator knowledge-based reasoning for situation assessment and accident diagnosis. Another paper provides the modeling techniques of the impact of problem solving tendencies of different crews, and offers examples of simulation runs (Li and Mosleh, 2017). An upcoming paper discusses the modeling of Performance Shaping Factors (PSFs) and operator response variability, and provides a detailed example of to demonstrate the new features and capabilities and comparison with results of benchmark exercises with real operators.

Compared with manually performed human reliability analysis (HRA) approaches (Cooper et al., 1996; Gertman et al., 2005; Kirwan, 1994; Ekanem et al., 2016), a simulation approach like ADS-IDAC offers several advantages. It allows more realistic portrayal of the human-system interactions mainly by providing rich contextual information to the human model and by explicitly modeling the outcomes of the human-system interactions. Simulation approach to HRA enables much higher resolution in terms of human behaviors and their causes. It provides a direct way for leveraging many insights from cognitive sciences, experimental psychology, and human factors studies to model and simulate operator response and predict errors, including errors of commission. Simulated scenarios can be also compared with actual events and plant simulator observations to further calibrate the models and also provide explanation for the observed behaviors.

Obviously, the predictive quality of a simulation-based HRA depends on the degree of realism of the underlying model. Lessons learned from earlier simulation HRA approaches, Cognitive Environment Simulation (CES) (Roth et al., 1992), Cognitive Simulation Model

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(COSIMO) (Cacciabue et al., 1992), and earlier versions of ADS were applied to make the simulation model more humanlike. Key features that distinguishes ADS-IDAC 3.0 from the other HRA cognitive simulation models include: (1) attention is explicitly modeled and cognitive process resource limitation is explicitly accounted for in the simulation, allowing a more realistic operator behavior, compared to typical expert system behaviors. (2) A deep reasoning process was developed where the virtual operator dynamically builds up reasoning chains with multiple layers of inferences, with the depth of the reasoning is determined by the virtual cognitive resources-time and attention-allocated to each reasoning chain. During this process different reasoning chains merge together by the nodes in common, and form reasoning net.

For control room operators, forming an accurate situation assessment and correct diagnosis is crucial to have successful responses to accidents. A successful situation assessment depends in part on whether the operators promptly perceive the key indications that are important clues for the situation diagnosis, and whether they put the clues together to reach a correct diagnosis.

To model operator ability of timely perception of critical cues, it requires a realistic way of predicting the dynamics of operator's attention focus in accident scenarios. In a control room, there are many control panels displaying a large amount of information. For the operator to perceive an indicator, except auditory alarms, the indicator must be within the operator's visual field, which is determined by the operator's position, viewing angle, and gazing control. These are heavily dependent on the operator's attention and require the operator's initiative to read the indicator. Even for auditory alarms that can easily grab the operator's attention initially, further interpreting and explaining of the alarm still require operator's initiative.

To capture the process of integrating various cues to form a basis for situation assessment and diagnosis, it needs a model of cognitive reasoning. Heuristic reasoning provides direct connections between the observations and diagnosis of an accident. This type of heuristic reasoning was previously modeled in ADS-IDAC using a "mental beliefs" as the core of a diagnosis engine (Coyne and Mosleh, 2014a). However, in addition to heuristic reasoning, a more deliberative and effortful reasoning can also take place in the operator mind. Such reasoning relates the observed plant dynamics and applies knowledge to explain them. This is also characterized as a continuous process that often takes more than one reasoning step to connect a set of observed symptoms to the accident root cause. This deliberative knowledge-based reasoning tells the operator which indicator they need to check in order to move the investigation forward, and guides the operator's attention focus.

In order to fill these two gaps in the ADS-IDAC model, a reasoning module has been developed to simulate the intention-driven attention and deliberative knowledge-based reasoning. This paper describes the cognitive architecture of the reasoning module. ADS-IDAC has gone through an evolutionally process over the past 25 years with a number of software versions (Coyne and Mosleh, 2014a, 2014b; Smidts et al., 1997; Hsueh and Mosleh, 1996; Mosleh and Chang, 2004; Chang and Mosleh, 2007). These versions have some similarities as well as differences, both in capabilities and focus on different aspects of advanced HRA and dynamic PRA analysis. The research discussed in this paper has built on the foundations developed by Coyne and Mosleh (2014a, 2014b). The reasoning module has been implemented in the new version of ADS-IDAC program, referred to as ADS-IDAC 3.0. The previous version before the addition of reasoning module is referred to as ADS-IDAC 2.0

The reasoning module increases ADS-IDAC's predictive capabilities in three main functions: (1) It mimics the way operators use knowledge to explain the observed plant dynamics; (2) It employs a new algorithm to dynamically calculate a metric of operators confidence in their accident diagnosis; and (3) It simulates the operators' dynamically changing attention that is driven by the use of knowledge. The generated reasoning processes directs the virtual operator to actively gather needed information from the control panel, with the intention to monitor the plant state, explain the observations, or collect evidence in support of a diagnoses.

This paper is organized into 6 sections. Following the introduction, Section 2 gives an overview of the ADS-IDAC simulation platform. Sections 3 and 4 describe the architecture and infrastructure of the reasoning module, including the memory representation and the implementation of the cognitive processes. Several simulation examples are provided to demonstrate the features and capabilities of the reasoning model. Section 5 covers model validation using the simulation results of various scenarios. Section 6 summarizes ADS-IDAC 3.0 capabilities; Section 7 offers a few concluding remarks.

2. Overview of ADS-IDAC simulation platform

2.1. Description of the starting platform of this research

ADS-IDAC employs a thermal hydraulic model RELAP 5 to simulate a plant response, a human model (IDAC) to simulate operators' performances, and a control panel model for modeling the interactions between plant and operators. A dynamic simulation approach like ADS-IDAC has several advantages in studying HRA. It allows to capture the human-system interactions specifically by providing rich contextual information to the human model and explicitly modeling the outcomes of the human-system interactions. With its embedded models of a nuclear power plant, ADS simulates accident scenarios that form the context for the IDAC operator response model. ADS-IDAC platform simulates situational contexts that might lead to human failure events, and the generated operator actions in turn impact the key plant parameters and potentially change the trajectory of accident scenarios. It also allows to embed relevant theoretical and empirical findings from multiple disciplines (e.g. psychology) and accident reports into the simulation program as rules of behaviors, and to apply these rules to different accident scenarios at much refined detail level.

IDAC is an operator behavior model developed based on many relevant findings from cognitive psychology, behavioral sciences, neuroscience, human factors, field observations, and various first- and second-generation HRA methodologies (Boring, 2007). It models individual operator behavior in a crew context and in response to plant abnormal conditions. Each operator in the crew has their own role and profile. IDAC covers the operator's various dynamic response phases, including situation assessment, diagnosis, and recovery actions. The program provides IDAC module the values of the set of dynamically changing contextual factors (plant physical process parameters, system states, and alarm states). The IDAC crew model then tracks the operators' internal cognitive responses to the situation, and generates a dynamically changing mental model of the situation, and resulting cognitive behaviors or physical actions.

At a high level of abstraction, IDAC is composed of models of information processing (**I**), problem-solving and decision-making (**D**), and action execution (**A**) of a crew (**C**). Given incoming information, the crew model generates a probabilistic response, linking the context to the action through explicit causal chains.

Fig. 1 is a schematic representation of the main elements of the IDAC modeling concept and its key elements in form of the umbrella I-D-A dynamic loop for each member of the crew. IDAC is composed of (1) a Problem-Solving Model, (2) Mental State as Engine of Cognition, (3) Memory and Knowledge Base Model, (4) Casual Model of Internal and External Performance Shaping Factors. Cognitive engine of IDAC combines the effects of rational and emotional dimensions forming a small number of generic rules of behavior that govern the dynamic response of the operator. The architecture of IDAC is such that its main modeling elements can be repeatedly embedded in a layered and progressively detailed representation of the cognitive process.

The ADS-IDAC simulation program is the integration of the IDAC crew model with ADS Dynamic PRA computer code. It contains six modules Fig. 2). The User Interface Module enables the user to edit the