Using Microworlds to Support Dynamic Human Reliability Analysis

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Abstract: Human error data is invaluable for validating low probability events, in the absence of operation plant data, in existing traditional static HRA approaches, but it is also crucial for advancing computer-based dynamic human reliability research. Probabilistic risk analysis, with the aid of advanced simulation tools, such as RELAP5-3D, has outpaced the simulation capabilities of existing HRA methods. Human error data can be used for the development of a virtual human operator model, which is fundamental for bridging the gap between existing probabilistic risk and the newly emerging field of computation-based human reliability analysis (CoBHRA). The Rancor microworld is a simplified process control which is sufficiently simple to allow participants to successfully configure the plant and begin producing electrical power after as little as half an hour of training. Rancor is well suited to gather human error data, which can then be used to build a virtual operator. Currently, Rancor is being used to gather data on human error probabilities within the context of performance shaping factors. An error seeding method is proposed, in which participants follow manipulated procedures to induce errors and require the participants to reconfigure the plant within the normal operating envelope.

Keywords: HRA, Microworld, Human Error, Error Seeding

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1. INTRODUCTION

Many [1], [2], [3] have chronicled the need and importance for simulation based modeling in human reliability analysis (HRA). Incorporating the dynamic characteristics of human performance into existing HRA frameworks is perhaps the largest driving force behind the impetus towards simulation and modeling in HRA. However, equally important is the need for accurate estimations of the human error potential that can ultimately be included in a probabilistic risk assessment (PRA). The field of HRA suffers from a dearth of empirical data needed to provide a suite of accurate quantifications of human error probabilities (HEPs) associated with a core set of human operations, decisions and actions, which are sufficiently flexible to be applied to different HRA domains. Together, capturing the dynamic element of human performance with a flexible set of human performance operations represent the Holy Grail of HRA research. The emergence and rapid advancement of computation-based simulation offers an avenue to acquire these key HRA elements and could advance the field substantially. This paper introduces a preliminary line of research and an accompanying framework using a microworld simulator to capture basic human error data applicable to nuclear process control and oil and gas domains.

Leveraging simulation and modeling through computation-based HRA is critical to bridge the gap between the more dynamic or computation-based PRA and the predominantly static or worksheet-based HRA methods available. Dynamic PRA has at its disposal cutting edge simulation tools, such as Reactor Excursion and Leak Analysis Program (RELAP5-3D) [4] to simulate plant failure conditions. This has been an invaluable tool to generate data used to provide accurate quantifications for component failure probabilities. In contrast, the available tools for generating meaningful data to quantify HEPs are less numerous and certainly less mature. There are some notable human performance modeling simulation tools worth mentioning such as the Adaptive Control of Thought Rational (ACT-R 5.0) [5], Cognitive Environment Simulation (CES) [6], Man-machine Integration Design and Analysis System (MIDAS) [7], Operator-Plant Simulation Model (OPSIM) [8], and the Accident Dynamics Simulator-Information, Decision and Action in Crew system (ADS-IDAC) [9]. Neither MIDAS nor ACT-R have been fully implemented for HRA. However, ADS-IDAC has been partially implemented for HRA and this attempt at simulation-based human performance modelling represents the most comprehensive and mature simulation environment used for dynamic HRA to date.

The authors propose a microworld simulator environment platform, termed Rancor, for use as a means to generate the much needed data to derive accurate human error probability estimations for use in both dynamic and static HRA methods. The dynamic HRA approach used to model human performance in a simpler manner than ADS-IDA in an attempt to make it more feasible to conduct dynamic simulation based HRA research. This paper will describe the simulator environment and how it can be used to support HRA efforts. Using a microworld to collect HRA data has been previously suggested and implemented [10], [11]. This paper uniquely ties the microworld data collection back to informing dynamic HRA.

2. ANIME FRAMEWORK AND MICROWORLD APPROACH

The ANIME Framework is a simulator and HMI platform representing a collection of software modules and capabilities developed over several years in support of full-scope simulator and microworld based research efforts [12], [13]. The ANIME framework itself is based on a Windows Presentation Foundation framework, but it also includes a suite of dynamic link libraries and custom user controls. The ANIME framework is quite flexible and easily tailored for different use cases. It was originally developed as a prototyping tool for nuclear process control digital control systems as part of operator in the loop design studies focusing on developing effective human-system interfaces (HSIs) [14], [15]. These design studies were completed at the Idaho National Laboratory in the Human Systems Simulation Laboratory, which is a full-scope, full-scale, and fully reconfigurable simulator capable of virtually representing nuclear power plant control rooms. ANIME has a giiNet application programming interface (API) which allows it to interface with the generalized pressurized water reactor (gPWR) simulator, which is a generic nuclear power plant simulator available to researchers that sidesteps many of the proprietary information issues associated with plant specific simulators. This API allows the ANIME framework to display plant parameters from gPWR as well as provide input to the simulation to afford prototyping of control systems. ANIME has also been interfaced to four proprietary plant simulators.

In addition to its use as a full-scope simulation HSI prototyping tool, the ANIME framework has been adapted to support a standalone microworld simulator [16], [17]. The Rancor microworld (see Figure 1) simulates a simplified pressurized water nuclear reactor process comprised of a nuclear reactor core that provides the heat source for a gamified water-based Rankine cycle simulation. In fact, the name *Rancor*, bestowed upon the microworld, was formed by combining the first part of the term *Rankine* with an abbreviation of the term *core* to denote a nuclear reactor core as the boiler within the Rankine cycle. The water-based Rankine cycle is a mathematical model describing the energy and associated phase changes of a fluid to vapor to convert the thermal energy from steam into mechanical energy used to spin a turbine and generate electricity. The underlying thermal hydraulic simulation in the Rancor microworld diverges from a general water-based Rankine cycle to simplify the system in accordance with the principles of gamification.

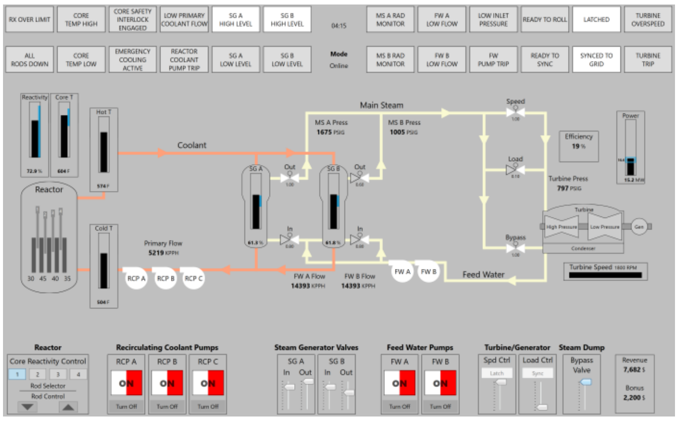

Figure 1. The Rancor microworld simulator.

The thermal hydraulics of the simulation follow a gamified Rankine cycle that resembles the design of a small modular reactor. The model follows basic physics, such as conservation of mass and enthalpy. The core coolant heating and enthalpy losses as the coolant flow through the primary loop rely on difference equations and are parameterized using realistic units. The state change and flow dynamics are largely gamified with little to no fidelity beyond conserving mass.

Control of the process resides with the participant; however, a system of interlocks and alarms keeps the plant within a well-defined operating envelope. The interlocks ensure the participant cannot move the plant into an unrealistic configuration and keeps the scenario within a specified band to ensure that the participant can always recover without breaking the simulation. For example, the reactor vessel has a high-temperature set-point to automatically scram the reactor to prevent the reactor vessel temperature from rising to an unfeasibly high-level. In addition to placing limitations on specific component values, the interlocks also ensure the participant cannot operate the plant in nonsensical ways, such as attempting to sync to the grid without the turbine at the required 1800 RPM necessary to produce electricity at the standard 60Hz (with a 4-pole generator). Without this protective setup of interlocks, operators could move the plant into unrealistic configurations, such as the core temperature being raised to unfeasible temperatures, if the participant controlling the plant did not provide adequate primary or secondary flow. The interlocks also enforce that certain permissives must be met to put the plant into some control conditions. These permissives are linked to annunciators to convey the current state, such as the annunciator that illuminates to denote the turbine is latched. Additionally, the annunciators arranged in panels at the top of the interface notify operators when certain plant indications are outside normal operating boundaries, if safety systems have engaged. Other microworld environments we have developed have incorporated set-point controllers and decision support systems that would notify operators to take action in advance of indications moving past alarm set-points [18].

The training and practice required to learn to operate the Rancor Microworld is greatly reduced by using the simplified simulation. The time-course for the simulation was also compressed to allow for the participant to interact with the Rancor Microworld in short durations. This gamification principle of compressing the time-span for a process is advantageous because it affords greater opportunity to collect data on the same process, but over a much shorter time-span. Indeed, pilot testing revealed that undergraduate psychology student participants can learn and operate the simulation at desirable competent levels after as little as forty minutes worth of training.

The Rancor microworld also contains experimental administration modules used to run participants through trials. Some of the capabilities afforded by these modules include the ability to configure a starting state for the plant model and insert faults at predefined time points or triggered by key process events. The Rancor microworld currently supports administering situation awareness freeze probes that can be linked to key events within the simulation, such as following turbine rollup or synchronization with the grid. Lastly, the Rancor microworld supports integration with eye tracking via commands to label events or control actions that can be sent to a linked eye tracking system.

2.1. Microworld HRA Approach

To support microworld HRA research, the ANIME framework follows a two-phased approach. Phase One concerns gathering empirical human error data from short duration simulation studies, which serve as vital inputs to the predictive models used in dynamic HRA. Phase Two consists of expanding upon the work of prior dynamic HRA efforts, such as ADS-IDAC, but building a simulation framework to perform the actual dynamic HRA analysis. The simulation can then be used as a tool for industry, regulators, and researchers to perform dynamic HRA for risk informed decision making.

To achieve Phase One of the microworld HRA approach, the Rancor microworld can be leveraged to capture much needed human performance data necessary to build predictive simulations. Human actions coupled with the plant control system and their associated underlying cognitive mechanism are based on the scenario context and performance shaping factors (PSFs). Several types of data are required as inputs to the human and system performance models. Models of the physical plant components and digital controls are matured, and several models are available to accurately represent the thermal hydraulic properties. Notably, RELAP5-3D has experienced extensive use in PRA to analyze accident events and estimate the incidence rate of core damage [4]. Human performance models are less mature and HRA, at least within the nuclear process control context, has always suffered a dearth of performance data to build these models upon. In order to provide a sound empirical and theoretical basis for the human performance model, several types of data are needed such as: the timing of decisions and actions performed by the crew, the type of information available to the crew given the context of the scenario, and the likelihood of success or failure to make decisions and actions. [19] provide a human error taxonomy based on Systematic Human Error Reduction and Prediction Approach (SHERPA) [20]. The SHERPA-based taxonomy serves as basic actions tied to Goals, Operators, Methods, and Selection rules (GOMS)-HRA. GOMS-HRA is a suite of task primitives with nominal timing and HEP values that can overcome the context specificity of the errors observed in full-scope simulator studies. Since full-scope simulator studies, which have difficulty eliciting sufficient errors for statistical analysis, typically rely on a specific plant and operators with experience from that plant, it is difficult to generalize the data to other contexts, let alone other plants with different configurations. The GOMS-HRA task level primitives can be used to decompose the specific task into basic units of analysis and provide empirical data to quantify the time required to perform these tasks and the probabilities of error associated with the task. GOMS-HRA task level primitives can be used to describe the vast majority of activities that occur within the control room and in the field at the plant (see Table 1).

Table 1: GOMS Task Level Primitives (TLPs)

TLP	Description
A_C	Performing required physical actions on the control boards
A_F	Performing required physical actions in the field
C_C	Looking for required information on the control boards
C_F	Looking for required information in the field
R_C	Obtaining required information on the control boards
R_F	Obtaining required information in the field
I_P	Producing verbal or written instructions
I_R	Receiving verbal or written instructions
S_C	Selecting or setting a value on the control boards
S_F	Selecting or setting a value in the field
D_P	Making a decision with procedure guidance
D_W	Making a decision without procedure guidance
W	Waiting

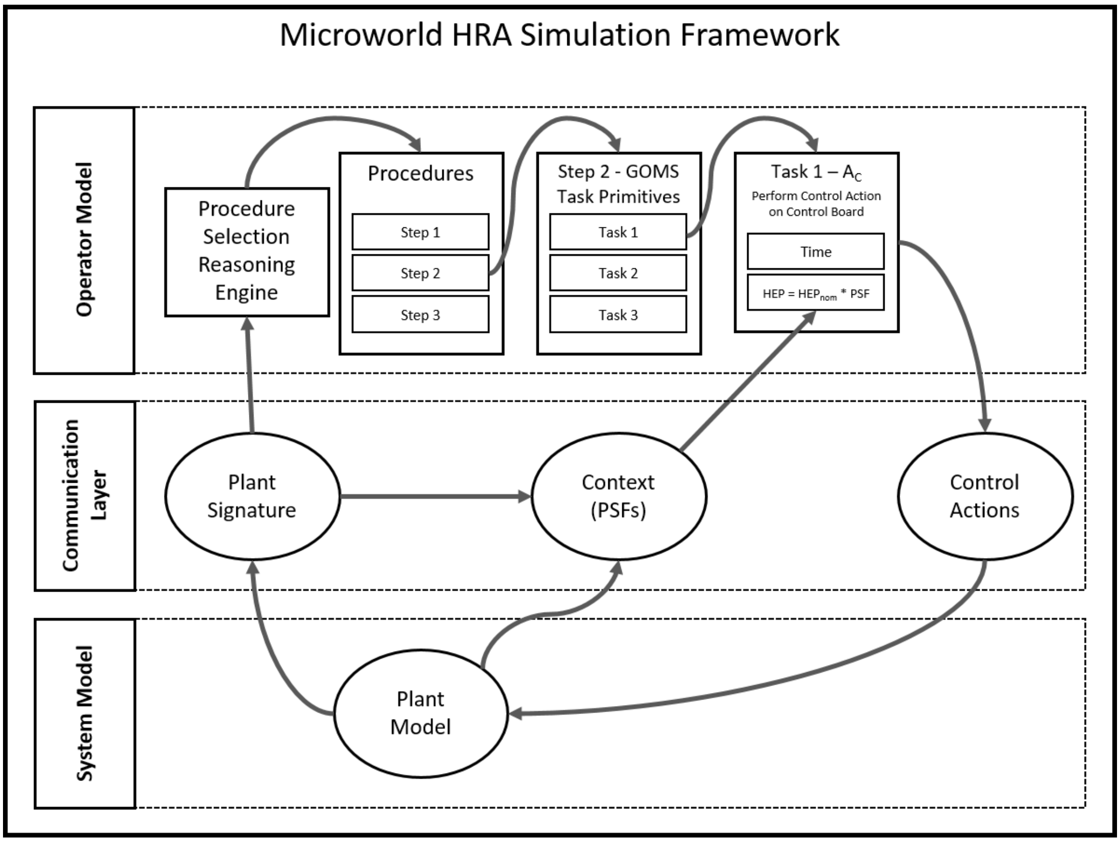

Figure 2: Microworld based simulation framework comprised of operator and system model connected through a communication layer.

Even with the GOMS-HRA task primitives to translate the context specific data from full-scope simulator studies into a more generic and usable form for human performance modeling, it is still quite challenging to empirically quantify human error with expert operators. Small sample sizes of operators and the limited trial runs performed with lengthy full-scope scenarios make it difficult to get sufficient data to accurately estimate human error in other control room contexts. The Rancor microworld provides an opportunity to evaluate a simplified representative scenario and capture the error rates exhibited by both novice and expert operators. For example, the participant’s decision and action responses to a component fault within each trial provide valuable data that can be used to identify empirical HEP estimates. Furthermore, the times to perform various actions are captured during the simulation, and therefore the timing data can be used in a manner to identify the time distribution concerning decisions and actions taken by the participant. Prior research efforts by the authors have used the timing data in conjunction with GOMS-HRA based human error rates to serve as human performance model inputs in a dynamic PRA simulation using the RELAP5-3D based RAVEN platform [21], [22]. Using this GOMS-HRA approach in conjunction with the Rancor microworld, it is possible to run many trials over a short duration to yield enough performance data to provide good estimates of the human error potential and the timing of decisions and actions.

The second phase of the microworld HRA approach entails building a simulation framework that is capable of performing dynamic human reliability analyses. A dynamic HRA simulation is useful for both retrospective analysis of prior events as well as a tool for prospective analysis to identifying risk significant contexts and events that could lead to severe incidents and accidents. Retrospective analyses are necessary for validating the simulation tool as an accurate representation of the human performance and system behaviors within the context of known events. Prospective analysis is far more valuable for industry and regulators since running predictive models of potential accident scenarios serves as a screening tool for risk informed decision making so that utilities can focus their resources on protecting against the most likely potential issue.

The microworld HRA approach requires several simulation capabilities or modules. In prior efforts, RAVEN acted as the communication layer and RELAP5-3D served as the plant model. This approach was successfully used to simulate a station blackout scenario [23]. To extend the dynamic HRA work beyond these prior efforts relying on RELAP5-3D, the ANIME framework's simulator giiNet API can be used as the communication layer to link the operator model with the full plant gPWR model as can be seen in Figure 2. The advantage of this approach is that gPWR also incorporates numerous control systems with an underlying plant model. These control systems provide automated actions in the form of interlocks and automatic plant responses that are not included in RELAP5-3D. Both approaches have advantages, with RELAP5-3D serving as a simplified and therefore faster simulation to perform, while the gPWR approach may better capture the nuances of actual plant operations at the expense of slower simulation iterations. Both of these complimentary approaches are currently being pursued.

The procedure engine, capable of recognizing plant signatures and correctly selecting the appropriate procedures given the signature, is a vital component of the simulation framework. Once the appropriate procedure step is identified, then the procedure can be decomposed into GOMS task level primitives. Then each task level primitive is executed, which entails waiting until the time for the task level primitive has elapsed. The plant context is used to estimate PSFs at the start of each task level primitive execution, which modifies the nominal HEP associated with the current task level primitive, to yield an HEP that represents the likelihood of failing to execute the task level primitive. If failure results, the task level primitive is repeated until success is achieved or the plant state has changed such that the current procedure step is no longer applicable and a new procedure must be begun. The overall process repeats until a normal operating envelope can be achieved or core damage results.

3. DISCUSSION

To support HRA efforts, this paper describes a two phase approach in which a microworld can be used to first collect human error data and then use this data in conjunction with simulation techniques to advance the field of computer-based dynamic HRA. Human error data is needed to validate the estimations and assumptions posited by existing traditional HRA methods. The Rancor Microworld is a useful tool capable of quickly and easily collecting this much needed human error data in its current standalone configuration. The capabilities of the Rancor Microworld and the ANIME framework it is built upon, can then be used to perform dynamic HRA simulations using a full-scope plant model to examine numerous plant accidents and events.

The simulation provides valuable timing and success or failure characteristics of a given scenario, which can then be used for risk informed decision making. Ongoing development and research is underway to leverage Rancor to capture more data to enhance the validity of the microworld HRA simulation, and the modeling capabilities of the simulation are being extended to support FLEX activities following a station blackout scenarios.

4. DISCLAIMER

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