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Dynamic Human Error Simulation of Work as Done – Modeling Procedure Deviations With Empirically Derived Failure Mechanisms

Thomas A. Ulrich[1], Ronald Boring[1], Jisuk Kim[1], and Roger Lew[2]

[1]Idaho National Laboratory, Idaho Falls, ID 83415, USA
[2]University of Idaho, ID 83844, USA

ABSTRACT

Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER) is an Idaho National Laboratory software tool developed to support dynamic human reliability analysis (dHRA). The software performs Monte Carlo simulations of a virtual operator performing procedurally prescribed tasks within the context of a dynamic and coupled nuclear power plant model. Changes in the plant state impact what tasks the operator must perform and vice versus. HUNTER supports a suite of scenarios with models containing procedures and corresponding human performance context parameters such as loss of feedwater and steam generator tube rupture scenarios. The procedure module contains a single path of steps to mitigate the faults within the two scenarios. Failures occur if the dynamically calculated human error probability (HEP) value exceeds a chance value for any given task or if the elapsed time to complete a task exceeds the allowed time for that task. In reality, reactor operators deviate to the wrong path due to their errors. To improve accuracy, HUNTER needs to be able to allow the virtual operator to incorrectly deviate along the wrong procedure path due to a diagnostic or understanding errors in addition to the existing HEP and time failures. Procedure deviations are errors of commission which are quite challenging to model since there are theoretically infinite errors of commissions that could be made at any point in the simulation. Empirical data collected from a recently performed study evaluating computer-based procedures and failures to adhere to the prescribed procedure steps were used to realistically constrain the possible deviations to a manageable set that could be modelled within the HUNTER simulation. The process to analyse the empirical procedure adherence data and develop generalized forms of the empirically observed failure mechanisms are described along with their implementation within the HUNTER simulation. Future work aims to continue to validate these failure mechanisms outside of the specific context of the loss of feedwater and steam generator tube rupture scenarios to understand their generalizability to other scenarios and to more accurately model work as done within nuclear process control.

Keywords: Hunter, Human reliability analysis, Computer-based procedures, Human error, Work as done

INTRODUCTION

Increasing nuclear industry interest in digital control rooms is driving increasing adoption of automation in tandem, which requires research on how these digital technologies impact human performance. Computer-based procedures (CBPs) are a unique form of automation that encompasses many of the types of relevant control room automation features (Boring, Ulrich, and Lew, 2023). Furthermore, these individual automation features must be integrated appropriately within the CBP as it becomes the central human-machine interface of the new digital control rooms. Traditional human factors research has investigated design principles; however, CBPs have only briefly begun to penetrate the main control room, at least within the U.S. commercial nuclear industry. As such, there is much more research needed on nuclear domain CBPs to ensure utilities have the proper guidance to develop effective site-specific deployments of CPBs with the NUREG-0711 *Human Factors Engineering Program Review Model* regulatory framework (O'Hara, Higgins, & Fleger, 2012). Dynamic human reliability analysis (dHRA) focusing on CBPs provides a unique and synergistic approach for advancing our understanding of human factors within future digital control rooms. This paper presents a novel approach to evaluate CBPs while simultaneously developing new dHRA methods, specifically the Human Unimodel for Nuclear Technology Enhanced Reliability (HUNTER; Boring et al., 2022) that can evaluate the digital control rooms including new forms of automation and their impact on the operator roles, responsibilities, and reliability.

DIGITAL CONTROL ROOMS

Current nuclear control rooms for the existing fleet of U.S. light water reactors have avoided digitizing their instrumentation and controls for the simple reason that there is little economic incentive to do so. Control room modernization itself does not afford greater efficiency, at least in the short term. Furthermore, it is expensive, logistically challenging, and has significant regulatory risk for the licensee. However, equipment obsolescence and rapidly evolving grid infrastructure are driving plants to reconsider adopting digital control room technologies. Antiquated analog instrumentation is no longer available and must be replaced by a digital counterpart. Renewable energy sources like wind and solar have induced greater grid dynamics that increase volatility of whole sale electricity markets such that base load power generation is much less economically viable than when the plants were first commissioned. The industry has begun to look towards alternative revenue streams such as supplying process heat for industrial applications which requires plant modifications and modern digital control systems (Ulrich & Boring, 2022; Ulrich et al., 2021). Perhaps most notably, the emergence of advanced reactors is a primary driver promoting the shift towards the adoption of digital technologies for nuclear power. In both the conversion to and initial implementations of digital control rooms for existing or advanced reactors, the digital technologies necessitate new regulatory methods to support vendors selecting and deploying control rooms for subsequent review by the U.S. Nuclear Regulatory Commission. To establish safety cases, one of the areas that must be addressed is establishing robust and reliable probabilistic risk analysis methods that can model and evaluate human error within a digital control room context.

DIGITAL CONTROL ROOMS AND AUTOMATION

Automation used in digital control rooms can broadly be delineated as control and information automation (Boring, Ulrich, and Mortenson, 2019). Control automation describes activities or tasks performed by the system on behalf of the operator. Information automation describes the gathering of data and synthesis into actionable information for an operator. Each definition defines the function performed by the system in relation to the operator to reveal an associated spectrum or level of automation defined as the relative task division between the human and the system (Sheridan & Verplank, 1978). This can ran range from the operator performing all tasks manually to a fully autonomous system performing all tasks without any operator intervention. The relative allocation of tasks for any system should be determined based on the concept of HABA-MABA or "Humans are better at/Machines are better at" in which the optimal agent is assigned the task (Fitts, 1951).

Within the digital control room context, distributed control systems (DCS) integrate sensor and controller data for analysis and presentation to the operator typically via a hierarchical multi-windowed display embedded within a vertical control panel or a desktop workstation. Control automation is employed to unburden operators from tedious, repetitive, and error prone tasks in lieu of supervisory control, in which the operator selects a system goal and allows the system to perform the nuanced control actuations to achieve the goal state. The role of operator shifts towards selecting the optimal goal states based on information automation. Information automation can make use of the burgeoning field of artificial intelligence to extract patterns with machine learning algorithms to characterize the state of the system and even predict future states of the system. Desktop workstations eliminate the need for operators to walk around the control room to acquire indicator values from the various control panels. Instead, the indications are arranged into a series of windowed displays. This multi-windowed arrangement no longer requires physical movement around the control room, but instead requires the operators to identify and then navigate to the appropriate display to find the information. Automation can ease some of this burden by cleverly synthesizing information and intelligently cuing the operator to the appropriate display; however, imprudent implementation of automation represents a significant failure point that could induce significant human error.

DYNAMIC HRA FOR DIGITAL CONTROL ROOMS

Human error modelling is fundamental to a successful adoption of digital control rooms for both existing and advanced reactors. Models of human error can directly inform the human-machine interface (HMI) design process as vendors approach deployment and begin developing digitally based concept of operations. Many advanced reactor vendors are pursing designs with passive safety features that preclude the need for much of the existing manual actions performed by operators in existing nuclear power plants. These designs also aim to leverage autonomy to further reduce any required human intervention, with the lofty goal of full autonomy eliminating the operator role entirely. HRA serves a critical function for either outcome and is particularly important in the near term to benchmark potential automation risk and reliability against the extensive established reliability observed for current operations. The methods support the progression towards greater autonomy in advanced reactors, but existing plants without passive safety capabilities will still rely on human operations within their digital control rooms.

In regard to the path for eliminating the human operator, high automation levels are rarely if ever achieved at the initial system deployment, as evidenced in surrogate domains such as aviation and surface transportation. The prudent approach entails incrementally introducing additional types and increased levels of automation in the digital control rooms as confidence in the systems grow. Indeed, existing plants reported this as their intended approach when surveyed about their strategy for control room modernization (Joe, Boring, & Persensky, 2012).

HRA serves the role of qualitatively and quantitatively benchmarking human performance to establish reliability targets the autonomous systems must achieve or exceed during each of these incremental progressions. Furthermore, initial prototypes performing function allocation can use dHRA to make risk-informed human or automation function allocations. Lastly, human oversight and intervention during each progressive stage must be analysed to ensure the configuration meets risk requirements. This hybrid configuration is similar to what existing nuclear power plant control rooms are experiencing as they begin to pursue their piecemeal adoption of a digtal control room.

Achieving true autonomy may not actually be a realistic goal, and that is why the term highly automated has been used to describe the goal state for advanced reactors. Indeed, it is quite difficult to envision a scenario where there is no role for a human operator, and more than likely humans will provide oversight of advanced reactors, albeit from a fundamentally different paradigm. Existing methods may not be adequate to model the new oversight role. For example, future digital operations centers will likely incorporate advanced digital supervisory control concepts such as human-robot autonomy and artificial intelligence. HRA methods must begin considering these new concepts. Efforts to digitize existing control rooms as well as initial efforts to develop advanced reactor control rooms provide some insights into the types of automation HRA methods must consider.

COMPUTER-BASED PROCEDURES FOR DHRA

CBPs represent a special form of automation within the digital control room context. NUREG/CR-6634 classifies different levels of CBPs (O'Hara et al., 2000) based on supported automation features. The most automated variant includes live data values of process parameters and soft controls to manipulate the system organized within a procedure structure that allows the crew to navigate through complicated sequences of tasks and governing logic that dictates the path the crew should follow. As such, CBPs represent the bulk of the existing analog control room elements along with the task structures in which those elements are used. This holistic representation makes them a useful tool for HRA methods. The remainder of this paper focuses on computer-based procedures and how they can be used by HRA to capture human performance data and improve our ability to model virtual human operators for dynamic HRA. A prototype empirical computer-based procedure (eCBP) developed to capture human performance data within the context of a dynamic plant state was developed. The rationale for eCBP, implementation details, and the proposed data collection strategy are discussed.

DATA COLLECTION FOR DHRA

Traditional static HRA performs time-invariant analysis of human failure events to derive human error probabilities (HEPs; Liinasuo, Karanta, & Kling, 2020). These HEPs are then used within a larger probabilistic risk assessment to characterise overall nuclear power plant risk profiles. Dynamic HRA provides a method to derive HEPs while reducing the subjectivity associated with the static methods. To perform a dHRA, Monte Carlo simulations are used of a virtual nuclear power plant and virtual operator(s) interacting with the plant while resolving some initiating event in the form of a malfunction within the plant systems.

Idaho National Laboratory has been developing a dynamic HRA method called the Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER; Boring et al., 2022; Ulrich et al., 2022). The unimodel term signifies the simplistic approach to rely on procedures as the driving mechanism for virtual operator tasks performed within the simulations. Performance shaping factors and GOMS-HRA primitives (Boring et al., 2017), representing the most basic task elements used as a dictionary to decompose procedures into basic elements, capture the HEPs and task time respectively. The plant state acts as context to manipulate these values to alter the error rate and speed of execution. Lastly, actions taken by the operator and the natural progression of the physical process within the plant model interact with the procedure logic to govern the potential activities the virtual operator performs as the simulation ensues.

Recent HUNTER development activities aimed to incorporate dependency mechanisms. Dependency is an elusive and nebulous concept to operationally define within HRA; but the notation of dependency is intuitive to understand, with a very simple conceptual definition of "error begets error" (Blackman and Boring, 2018). Toward the goal of deriving a HUNTER simulation mechanism to model dependency, previously collected empirical data (Boring et al., 2023) collected from the Rancor Microworld Simulator (Ulrich et al., 2017). Rancor was modified with an initial CBP that both guided student "operators" and logged plant process parameters, operator actions on the plant, and operator interactions with the CBP (Ulrich et al., 2022). The analysis found evidence of dependency within the empirical trials representing single scenarios developed to emulate a potential human failure event sequences. It was unable to uncover the specific mechanisms due to a lack of data; however, it revealed the significant potential for CBPs as a tool to record empirical data for HRA.

Scenario-based data collection has precluded the collection of data samples of sufficient size to support the development of dHRA models. Historical approaches rely on full scope training simulators with expert observers coding operator actions in relation to know goals of the scenario to evaluate HRA human performance metrics. As a result, the data are challenging and tedious to convert to units of analysis of sufficient resolution to extract generalizable error metrics that can be applied outside of the specific context evaluated in the scenario. HUNTER, by using GOMS-HRA, provides the method to quantify small units of analysis from scenarios to generalizable tasks that can be used to characterize other contexts. GOMs-HRA provides a collection of fundamental operator tasks called GOMS-HRA task level primitives. Each of these primitives has a nominal human error and time distribution representing the length of time required for execution of the task. The CBP collected data provides the context and task objectives within step level units of analysis, i.e., step epochs, which provide the ability to evaluate the appropriateness of the operator actions or lack of actions at a high level of detail to quantify GOMS-HRA primitives that can then be used by HUNTER in dHRA simulations.

Significant post hoc analysis was required to create step epochs from the raw data. In this context, epochs were created for step and procedure units of analysis. The post processing compiled the relevant plant planters and operator actions and evaluated those against the procedure logic to output HRA error categories as described in Table 1 below. Initial classification attempted to use the traditional HRA metrics of correct, error of omission, and error of commission. However, the traditional categories proved insufficient to characterise the types of operator actions or lack of actions observed within the context of the step epochs.

Table 1. HRA human error categories used to characterize operators actions or absence of actions while following procedures governing operator response tasks to the plant state.

	Dimensions			**Level**	
Tradition Metrics	***Prescribed***	***Ordinal***	***Executed***	***Step***	***Procedure***
Correct	✓	✓	✓	✓	✓
Error of Omission	✓	✓	✗	✓	✓
Error of Commission	✗	✗	✓	✓	✓
Proposed Metrics					
Error of Sequence	✓	✗	✓		✓
Discretionary Commission	✓	✓	✓		✓
Discretionary Omission	✓	✓	✗		✓

The unit of analysis for epochs is a crucial element to this analysis and the rationale for additional HRA error metrics proposed here. Within each epoch, procedure-prescribed actions were defined as actions explicitly stated within the step. Evaluating the operator response is straightforward within step epochs, and these can be characterised by the traditional HRA metrics. It is possible to use a strict interpretation of the traditional metrics and apply those at the procedure epoch level, but this overlooks much of the nuance revealed while analysing the data for dependency relationships. Procedure epochs require additional categories to characterise deviations that are appropriate based on the plant conditions and prior operator actions but are not explicitly defined as such within the procedure, which can be defined as the contrast between "procedure completion as prescribed versus as performed."

To improve accuracy, HUNTER needs to be able to allow the virtual operator to deviate along the wrong procedure path due to diagnostic or understanding errors in addition to the existing HEP and time failures. Procedure deviations are errors of commission that are quite challenging to model since there are theoretically infinite errors of commissions that could be made at any point in the simulation. The deviations from the prescribed procedures can greatly expand the fidelity of our dynamic HRA models since they now provide potential error of commission mechanisms that also support recovery and consequently dependency modelling.

A set of error mechanism algorithms must be developed based on empirically derived probability distributions. Errors of omission are not challenging to model, since a nominal probability for missing a particular step can be estimated. Errors of commission cannot be as easily derived since there is no bound to what could be erroneously performed by the operator. Instead the error of sequence, discretionary commission and discretionary omission serve as error mechanisms analogous to the collective category of error of commission. Additional research is needed to collect the data to define the probabilities and time distributions for specific instantiations of these observed error mechanisms within the GOMS-HRA framework. An experimental CBP can serve as tool to collect these data, but it is not within the feature set of typical CBPs to collect such data.

PROPOSED COMPUTER-BASED PROCEDURE FOR HRA DATA COLLECTION

Commercially deployed CBPs are typically configured for the application without any or with highly limited customization. This is intentionally done to ensure consistency across operators. Commercial CBPs include an approved suite of automation features collectively implemented to enhance performance. As a result, a commercially configured CBP has limited utility to understand the nuances of individual automation features as they impact operator performance. A system evaluation of these individual features and combinations of features requires a configurable CBP explicitly designed to evaluate human performance impacts. Figure 1 shows the proposed CBP system coupled with the Rancor Microworld Simulator during a simulated startup procedure.

For illustrative purposes, one automation feature demonstrates how automatic features eliminate the ability to evaluate human performance and the subsequent challenges of isolating and evaluating individual feature impacts on performance. As can be seen under Step 1 within Figure 1, each substep provides a button containing a descriptive link to the next required procedure item based on live plant status and procedure logic. Selecting this button automatically moves the active element to this prescribed item. As such, it is not possible to deviate from the prescribed path of the procedure, and errors cannot be evaluated for navigation within procedure elements. There have been paper based procedures that can identify navigation errors, however these are limited and the applicability to a digital system is unknown. Logically, the error prone navigation of paper based procedures is eliminated; however, the specific contribution of navigation errors to overall CBP-based human error is not understood, since the digital format of the procedure and the linked automation features mask easy identification of other errors in procedure following.

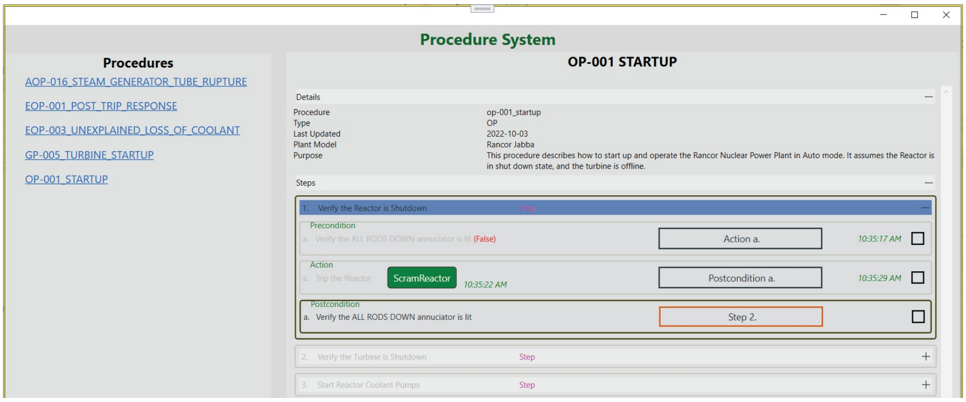

Figure 1: Computer-based procedure developed to systematically evaluate human performance at a resolution unit of analysis for populating HUNTER model elements with timing distributions and human error probabilities.

Teasing apart individual error probabilities for automation features that eliminate those errors may initially appears superfluous. After all, the error mode has been eliminated in the solution. Nonetheless, automation features often come at a cost to the operator skills and knowledge in regard to the system as a result of the out-of-the-loop performance decrement. Automated navigation to the next element eliminates the need for the operator to track the logic of the procedure. As such, the operator loses their understanding of why each step may be performed. Additionally, locking operators into a prescribed path provides a consistent task execution; however, there may be novel instances when operators should deviate from the procedure. The ability for operators to override the procedure has been considered; however, the trade-offs associated with automatic navigation require additional investigation, since it is not possible to foresee all instances to provide varying levels of override capabilities. The customizable CBP thus provides a systematic method to evaluate this impact alone. Once individual automation elements can be understood in isolated experiments targeting their performance impacts, the next phase of experiments can then evaluate the interactions between the individual elements with systematic integrated automation feature experiments. These experiments also provide the highly related benefit of providing the means to obtain high resolution task and subtask level unit of analysis of human error across these individual automation features, which can then be used to populate GOMS-HRA primitives for dHRA modelling within HUNTER. This modeling capability can then be flexibly applied to advanced reactors with combinations of these features in their CBPs as well as more traditional control rooms, since the manual execution timing and errors would be captured as baseline performance when evaluating individual automation features.

CONCLUSION

CBPs serve a dual role within near-term HRA research. First, the CBP implementation itself is complex and requires a better understanding of how this relatively new technology impacts the operator task. Second, the CBP itself can be used as a tool to collect human performance data due to the context-providing capability the procedure provides, in which the procedure steps serve as epochs for high resolution units of analysis. Future work with a revised CBP is underway. The new CBP leverages the lessons learned from this initial dependency analysis. Mainly, the new CBP records the data and calculates many of the metrics that were manually calculated post hoc for the previous analysis. The customizability of the CBP was also enhanced to allow features that would typically never be included in a CBP deployed in a commercial setting. This is done to provide better experimental control over the manifestation of errors based on individual procedure features presence. For example, place keeping is one notable advantage of CBPs, but this may unduly restrict the possible types of errors. Manipulating place keeping provides a means to understand the utility of this feature as well as represent more traditional procedure place keeping in line with existing paper based procedures.

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