

Human Reliability Analysis for Digital Human-Machine Interfaces: A Wish List for Future Research

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Abstract: This paper addresses the fact that existing human reliability analysis (HRA) methods do not provide guidance on digital human-machine interfaces (HMIs). Digital HMIs are becoming ubiquitous in nuclear power operations, whether through control room modernization or new-build control rooms. Legacy analog technologies like instrumentation and control (I&C) systems are costly to support, and vendors no longer develop or support analog technology, which is considered technologically obsolete. Yet, despite the inevitability of digital HMI, no current HRA method provides guidance on how to treat human reliability considerations for digital technologies.

Keywords: HRA, human-machine interface, digital systems.

1. NEW CHALLENGES FOR OLD METHODS

A central goal for phasing in newer technologies is to ensure that a new system is at least as reliable as the system it is replacing. In terms of HRA, the goal is to ensure that operator performance using the newer technology is at least as reliable as performance using the older technology. Such a comparison may be made by estimating the human error probabilities of various human activities, including human failure events.

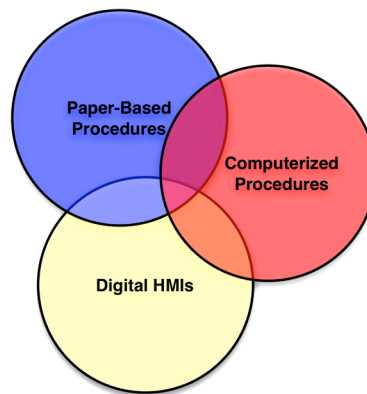
The challenge of new technology is that it, in many cases, is newer than the tools used to evaluate it. Such is clearly the case with human reliability analysis (HRA). NUREG-1792, *Good Practices for Human Reliability Analysis* (Kolaczowski et al., 2005), outlines a variety of HRA methods. Commonly used HRA methods currently in use in the U.S. nuclear industry include: THERP, ASEP, SPAR-H, ATHEANA, HCR/ORE, CBBDT, and the EPRI HRA Calculator. It is important to note that none of these HRA methods was explicitly designed to deal with digital HMI. At the present time, these HRA methods have also not provided supplemental guidance to explain how to use these methods to evaluate operator performance with digital systems.

HRA development is ongoing. Yet, many domestic and international development efforts center on creating refinements of legacy methods for new applications. For example, recent work to address HRA for fires (U.S. NRC, 2012) is closely based on ATHEANA, as is recent work on HRA for spent fuel handling (Brewer et al., 2012). Recent work in progress by the U.S. NRC to develop a cognitive framework for HRA builds heavily on CBBDT without specifically addressing new applications (Whaley et al., 2012).

Recent work at INL commissioned by the U.S. NRC has looked at specialty aspects of HRA related to computerized procedures (CPs; Boring and Gertman, 2012a) and small modular reactors (Boring and Gertman, 2012b). While both projects successfully produced guidance to assist the NRC in evaluating licensing submittals in this area, both projects shared the shortcoming that the underlying HRA methods failed to address digital human machine interfaces (HMIs). For example, HRA guidance for CPs must necessarily take into account: (a) human aspects of using traditional paper-based procedures, (b) unique human aspects of using the computerized procedures, and (c) human aspects of using a digital control system. Without a foundational tool for modeling the latter part—the human aspects of using the digital HMI—the HRA will be incomplete or inaccurate, thereby greatly increasing the uncertainty associated with the analysis.

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Figure 1: Relationship between CPs, paper-based procedures, and digital HMIs.



CPs represent a combination of factors related to traditional paper-based procedures as well as factors associated with digital HMIs. Figure 1 provides a representation of the problem space within HRA—CPs feature human error and success opportunities unique to CPs but also overlap to a certain degree with paper-based procedures and with digital HMIs. For example, as with paper-based procedures, it may still be possible to omit steps within CPs, but the likelihood is lower with most CP designs. CPs may feature additional checking of step completion, which has the potential to lower the frequency of skipped steps. However, the system is not without tradeoffs. Because in CPs the procedures are part of a software system, there is the opportunity for hardware or software failure, which represents a new failure mode not possible with traditional procedures. Additionally, performance issues known to occur in digital HMIs, such as loss of operator vigilance during automated actions, may also occur in CPs. Similar tradeoffs exist for other applications of digital HMIs.

The majority of contemporary HRA methods are linked to the empirical data basis in the original THERP method, released as NUREG/CR-1278 (Swain and Guttman, 1983), a method predating the advent of digital HMIs in the control room. While newer methods have attempted to improve on THERP with respect of treatment of cognition, context, and errors of commission (Boring, 2007), none have explicitly provided guidance on the types of human failure events that are related to digital HMIs nor updated the quantitative basis for those human error probabilities. As a result, method refinements addressing topics like CPs suffer from significant gaps, since a large portion of the human interaction with these systems centers on digital HMIs. Without an underlying approach for digital HMIs, current HRA approaches cannot adequately address control room modernization or advanced control room concepts.

THERP provides activity types that serve as lookup tables for nominal human error probabilities. In simplistic terms, the job of the THERP analyst is to match the scenario being analyzed to the best-fitting activity type in THERP. Digital HMIs introduce significant new technology both within and outside the control room. Just within the control room, there is significant digitization: features like soft controls, digital displays, computerized procedures, and automated actions may make it possible for reduced control room staffing or even, as some small modular reactor (SMR) vendors have suggested, a single operator to control multiple reactor modules. The problem confronting a human reliability analyst is that the unique aspects of the modern HMI cannot be readily accounted for in THERP. For example, THERP Table 20-11 provides “Estimated HEPs for errors of commission in check-reading displays” (Swain and Guttman, 1983). This table includes a single item for digital indicators as were seen in nuclear power plant control rooms in 1983, as well as an additional seven items related to analog meters. While it may be possible to backfit an analysis of digital HMI displays to such THERP tables, to do so clearly oversteps the original intent of the method as well as the applications for which it was intended.

Newer HRA methods may more readily generalize to the types of technologies and concepts of operation found in digital HMIs. For example, the SPAR-H method (Gertman et al., 2005), while

based on THERP (Boring & Blackman, 2007), eliminates the activity types and instead uses performance shaping factors (PSFs) for quantification. Performance shaping factors are influences on the operators' performance that serve to increase or decrease the HEP. Because an activity or task analysis is not explicitly required in SPAR-H, these PSFs seemingly move the analysis away from the activity type focus of THERP, but it must be remembered that the HEPs in SPAR-H are derived from THERP. Recent work by Rasmussen and Laumann (2014) reviews the suitability of the HMI PSF in SPAR-H for the computerized control rooms found in the petroleum industry. These authors conclude that it is necessary to modify the PSF assumptions and quantitative weightings before SPAR-H is applicable to such an application.

Second-generation HRA methods like ATHEANA (U.S. NRC, 2000) were developed out of a need to accommodate event scenarios and activity types that were not readily accounted for with methods like THERP. Thus, early work on ATHEANA featured a significant emphasis on low power and shutdown applications. Additional analyses showed the flexibility of the method to be used in analyses for unusual yet plausible events. The considerable flexibility of ATHEANA makes it an ideal candidate for use in new domains like digital HMIs. Given the considerable expertise required for an ATHEANA analysis, the application of the method to digital HMIs should not be undertaken casually, and additional guidance will be required for its use. For example, ATHEANA was recently adapted for use in scoping analyses for fire HRA events (U.S. NRC, 2012). Such explicit guidance helps to guide the ATHEANA analyst in a reasonable way for fire applications, but comparable guidance does not currently exist for the application of ATHEANA more generally to digital HMIs.

Because no HRA method was specifically developed for digital HMIs, the application of any current HRA method to digital HMIs represents tradeoffs. A first-generation HRA method like THERP provides clearly defined activity types, but these activity types do not map to the HMI or concept of operations confronting operators of digital HMIs. A second-generation HRA method like ATHEANA is flexible enough to be used for digital HMI applications, but there is insufficient guidance for the analyst, requiring considerably more first-of-a-kind analyses and extensive digital HMI expertise in order to complete a quality HRA.

Existing HRA methods will need to be adapted to adequately address digital HMIs, and new HRA methods will need to take digital HMIs into full consideration. Absent such development efforts, HRA guidance needs to be improved and developed in order to maximize the utility of existing HRA methods to digital HMIs. This paper presents a research proposal to address the deficiencies in HRA and redress the lack of coverage for digital HMIs. It is hoped that this paper may serve as an informal icebreaker toward beginning such research once appropriate participants and funding sources are realized.

2. A RESEARCH PROPOSAL TO ADDRESS DIGITAL HMI

This proposal addresses the need for HRA for digital HMIs in five crucial ways:

1. Conduct a systematic operating experience review of human errors in interacting with digital HMIs as documented by non-nuclear industries with significant digital HMI experience,
2. Identify human failure events (HFEs) specific to nuclear power plant control room operations using digital HMIs,
3. Establish those performance shaping factors that are unique to digital HMIs—these PSFs will need not simply be identified; the empirical basis for quantification needs to be established,
4. Perform a validation study using a research simulator on the effects of digital HMIs on reactor operator performance, and
5. Develop guidance for including and quantifying these HFEs in the HRA and PRA.

Each of these areas for research is discussed separately below.

2.1 Operating Experience Review

Hickling and Bowie (2013) recently completed a literature review that provided invaluable HRA data points on digital HMIs. This work is an example of tapping into available data that have not been tabulated into a meaningful way for use in HRA. An extension of such efforts is needed, using a wide variety of operating experience reviews. For example, a review of human errors in digital user interfaces might take advantage of two readily available sources of data:

- The Federal Aviation Administration (FAA) maintains a database of flight near misses. Many of the cockpit and air traffic control tower interfaces feature digital HMIs that mirror the types of safety critical operations conducted by control room crews in nuclear energy.
- Many software firms maintain databases of hundreds and, in some cases, thousands of usability study findings. A typical usability study consists of five to ten users engaged in a variety of scenarios with a novel HMI. Relevant data include error rates associated with particular HMI design concepts.

Both FAA and usability databases represent a significant and untapped source of human reliability data that can serve as the foundation for cataloging and quantifying human errors with digital HMIs.

While formal PRAs can adequately document those HFEs related to errors of omission—those required actions that operators fail to perform—it has proven difficult across the PRA community to identify errors of commission—those errors caused by an action inadvertently taken by operators. The use of FAA and usability data sources will serve as an effective way to anticipate errors of commission that can occur when using digital HMIs. No such account currently exists for use in HRA.

2.2 Human Failure Events with Digital HMIs

Once these data have been captured, it is necessary to categorize them in terms of their suitability for nuclear operations. A set of relevant HFEs needs to be identified based on an analysis of proposed digital systems in upgraded and new control rooms. To help identify new HFEs, research related to digital HMIs in the advanced control room at a new-build plant or an in-design plant like a small modular reactor should be reviewed.

Informal discussions with the PRA group at an SMR vendor has suggested the risk significant HFEs identified to date as part of the PRA licensing submittal have all centered on operator interaction with digital HMIs. While the vendor has adopted conservative screening values as part of their HRA, this choice is necessarily a reflection of the lack of ready HRA methods to conduct a valid, detailed analysis on HFEs related to digital HMIs.

2.3 Digital HMI as a PSF

The selection of performance shaping factors contained in current HRA methods like SPAR-H is tailored by existing analog nuclear power applications. It is anticipated that the most risk significant PSFs for digital HMIs may prove different than for traditional analog instrumentation and controls (I&C). For example, PSFs that typically drive errors may be mitigated in digital HMIs:

- *Time*: Tasks can be performed more quickly,
- *Workload*: Overall workload can be reduced,
- *Complexity*: Cognitive demands can be minimized,
- *Procedures*: Fewer errors may be made in transitioning through or between computerized procedures, and
- *HMI*: Information may be displayed in a more straightforward manner.

However, not all HMIs are equal, and the importance of having a nuanced PSF to account for the quality of the HMI or a particular facet of the HMI (e.g., legibility of text) may prove important to HRA (Boring et al., 2006). A good example of refining a PSF to account for digital HMIs can be found in Rasmussen and Laumann (2014).

A caveat is needed. The distinction is often made between internal and external PSFs (Gertman and Blackman, 1994). *External PSFs* represent those factors external to the individual that affect their performance, such as the HMI, procedures, or the environment. In contrast, *internal PSFs* are those factors within the individual that affect their performance, such as workload, experience, or stress levels. The distinction between internal and external PSFs is generally meaningless to most HRA methods in practice. The PSFs, whether internal or external, are treated identically by the methods. However, when generalizing the PSFs to new interface technologies, this distinction becomes crucial. Internal PSFs may be seen as largely invariant across technologies and domains. For example, the subjective experience of high workload is a psychological phenomenon that does not hinge on a particular technology. Whether the high workload is caused by analog instruments or multiple digital screens, the effect is similar in its effect on the psychological processes the operator undergoes. This universality is not the case with external PSFs. External PSFs reflect the external world with which the operator interacts. What is meant by the HMI can vary significantly from one domain to another and, indeed, from one technology to another. The proposed research should focus on documenting external PSFs.

2.4 Validation Studies

Where there are gaps between the data afforded by the operating experience reviews and the identified HFEs, relevant scenarios will be developed to study in a control room setting. Both Halden Reactor Project and the Korean Atomic Energy Research Institute have a successful history of running control room simulator studies to address HRA. As recent efforts have revealed, the data that can inform quantification is limited when using licensed reactor operators (Lois et al., 2009; Bye et al., 2011), and it may be desirable to augment full-scope simulator studies with microworld studies using non-licensed operators (Boring et al., 2012; Liu and Lee, 2014).

A reasonable approach to validating digital HMI assumptions for HRA would be to piggyback small validation components on existing human factors studies, such as those being performed on new control room interfaces developed through the Light Water Reactor Sustainability (LWRS) project at the Idaho National Laboratory (Boring et al., 2014). The expertise gathered in developing digital HMIs and running operator studies will translate to a seamless integration with HRA data needs. The use of Bayesian data analysis techniques can ensure that the data—while comprising a limited sample set—can inform HRA (e.g., Groth and Swiler, 2013).

2.5 Improved Guidance

While presented last in the list, developing improved guidance for existing methods may prove the practical starting point. As demonstrated in Boring and Gertman (2012a, 2012b), it is possible to use existing HRA methods for digital HMIs provided guidance is developed to help analysts extend the methods in a consistent and logical manner. The guidance in Boring and Gertman is not method specific, however, and more work needs to be done to apply methods to problems involving digital HMIs and then document lessons learned for successful adaptation. Some methods may be more amenable to such adaptations than others.

It should not be ruled out that insights from the operating experience reviews (e.g., Hickling and Bowie, 2013) could be used to provide supplemental worksheets to existing methods. It might well be possible, for example, to adapt the work in Hickling and Bowie to create a new THERP table specific to digital HMIs. HRA must not be frozen in time—a danger when it exists to support heavily regulated industries. Improved guidance is a natural way to ensure that our understanding of HRA methods adapts to the changing face of technology.

3. CONCLUSION

As noted throughout this paper, no existing HRA method adequately addresses digital HMIs. The proposed research in this paper, if realized, will yield empirically derived and validated results to help identify and quantify sources of human error for reactor operators using digital HMIs. The results should be tied to existing HRA methods for maximum utility by the industry and regulator. The proposed research is important in establishing a credible path toward incorporation of digital technologies—and their use by human operators—in risk analysis. Additionally, by aligning HRA with the same digital technology found in non-nuclear process control, the opportunity exists to attract new HRA funding from other safety critical industries like gas and oil, non-nuclear electrical production and distribution, and chemical manufacturing. These are industries poised to move into a more risk-informed framework, but their adoption of this approach is hampered by a lack of available tools. The proposed research moves HRA into new areas where it is clearly needed while addressing the biggest gap in current HRA methods.

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