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Guidance for Human-system Interfaces to Automatic Systems

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Automation is ubiquitous in modern complex systems, and commercial nuclear- power plants are no exception. Automation is applied to a wide range of functions, including monitoring and detection, situation assessment, response planning, and response implementation. Automation has become a "team player" supporting personnel in nearly all aspects of system operation. In light of its increasing use and importance in new- and future-plants, guidance is needed to conduct safety reviews of the operator's interface with automation. The objective of this research was to develop such guidance. We first characterized the important HFE aspects of automation, including six dimensions: Levels, functions, processes, modes, flexibility, and reliability. Next, we reviewed literature on the effects of all of these aspects of automation on human performance, and on the design of human-system interfaces (HSIs). Then, we used this technical basis established from the literature to identify general principles for human-automation interaction and to develop review guidelines. The guidelines consist of the following seven topics: Automation displays, interaction and control, automation modes, automation levels, adaptive automation, error tolerance and failure management, and HSI integration.

INTRODUCTION

A new generation of commercial nuclear power plants (NPPs) is emerging from technological developments in many engineering disciplines, such as reactor physics and digital instrumentation and controls. A number of potential human-performance issues associated with these new technologies have been identified and prioritized (O'Hara et al., 2008a; O'Hara et al., 2008b). Two of the highest-priority issues were related to automation: "Levels of Automation," and, "Interfaces to Automation." At the simplest level, an automated system is designed to accomplish a goal that might be predetermined by designers or set by operators based on their current needs. The automated system processes inputs from the plant and operators to meet the goal. Since automation can be applied to many different areas of plant operation, from analyzing procedure steps to controlling plant systems, the specific processes used to accomplish automation's goal may vary.

Modern approaches to automation emphasize the value of multi-agent teams for monitoring and controlling complex systems (Christoffersen & Woods, 2002; Hollnagel & Woods, 2005; Woods & Hollnagel, 2006). The teams consist of human, software, and hardware elements working together, sharing responsibilities, and shifting responsibilities to support the plant's overall production and safety missions. In this context, the term "agents" often generically refers to who/what is responsible for performing an activity. Functions are allocated to human or machine agents, or a combination of the two (shared responsibility).

The U.S. Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) aspects of NPPs to ensure that their design uses state-of-the-art HFE principles. These reviews help protect public health and safety by ensuring that operator's performance and reliability are supported appropriately. In light of the increasing use and changing nature of automation, the NRC's staff needs guidance to enable them to conduct safety reviews of it. Our objective in this research was to develop guidelines for reviewing the human-system interfaces (HSIs) for monitoring and control of automation. While our primary focus was on NPP applications, the principles and guidance developed are applicable to many other complex systems.

METHODOLOGY

The methodology used by the NRC to develop HFE review guidance is briefly summarized below. See O'Hara & Higgins, 2010 for additional information and detail.

Following the analysis of user needs (O'Hara et al., 2008b), a technical basis upon which to develop review guidance is developed. Our first step was to develop a characterization of plant automation. The characterization describes the design aspects of automation systems that are important to human performance. The characterization has to be sufficiently robust to accommodate the review of a diversity of automatic systems that designers may employ. Characterization is important because it affords a structure for developing and organizing the guidance. Also, it gives the reviewer a framework for requesting information during design safety reviews. To develop the characterization, we reviewed existing automated systems for several new plant designs, as well as systems outside the nuclear industry.

Once the characterization was completed, research findings pertaining to the effects of automation design on human performance was analyzed to identify issues and best practices for supporting performance. Information from a variety of sources was used. We reviewed existing HFE standards and guidance documents. However, little guidance is provided for the design of user interfaces for automation in most HFE standards and guidelines. One exception is the Federal Aviation Administration's *Human Factors Design Guide* which was updated to include guidance for automation (Ahlstrom, Longo & Truitt, 2002). We also sought chapters in HFE handbooks offering sound analyses and syntheses of existing literature (e.g., Lee, 2006). Such documents are invaluable in that they constitute a review of research and operational literature by knowledgeable experts. We then reviewed the basic literature, consisting of papers from research journals and technical conferences and operational experience with automation in the nuclear as well as other industrial domains.

The findings and conclusions identified from the literature review were then used to develop general principles for human-automation interaction and HSI design review guidance. In the next section we summarize our characterization of automation, the general principles that support human-automation interaction, and HSI guidance for monitoring and controlling automation.

FINDINGS

Characterization of Automation

We identified six independent dimensions along which automation can be characterized: Levels, Functions, Processes, Modes, Flexibility, and Reliability. Each is briefly described below.

Levels. The level of automation is the degree to which an activity is automated, extending from manual (i.e., performed by personnel without automation) to fully automated (i.e., performed with little to no personnel involvement). Many levels of automation taxonomies have been defined (e.g., Sheridan, 1992, 2002; Billings 1991, 1997a). We sought to fit NPP automation applications to a levels-of-control framework. Considering the diverse applications of automation used in the nuclear industry, the Billings' scheme seemed most appropriate with some modifications. Five levels of automation were defined. In Level 1, Manual Operation, operators manually perform all tasks. In Level 2, Shared Operation, automation performs some aspects of a task while operators perform others. In Level 3, Operation by Consent, automation performs when directed by operators to do so. Operators monitor closely, approve actions, and may intervene to provide supervisory commands that automation follows. In Level 4, Operation by Exception, automation performs all tasks unless specific situations or circumstances are encountered; in such cases, operators must approve of critical decisions and may intervene. In Level 5, Autonomous Operation, automation performs all tasks. Operators monitor performance and perform backup if necessary, feasible, and permitted. Sometimes NPP systems are characterized at one level, and, at other times another level is appropriate. For example, a computerized procedure may normally be used in Level 3, Operation by Consent, by executing a predefined sequence of procedure steps then stopping for operator intervention. However, under some circumstances, operators may want to control each step transition themselves and change the automation to Level 2, Shared Operation.

Functions of automation. In this context, functions refer to the cognitive functions or dimensions to which automation is applied, e.g., information acquisition, decision making, control (Endsley & Kaber, 1999; Kaber & Endsley, 2004; Parasuraman, Sheridan, & Wickens, 2000). We chose a classification that has been used as a basis for many NRC HFE guidance development efforts (O'Hara et. al, 2008a). It includes the functions of monitoring and detection, situation assessment, response planning, response implementation, and interface management. Monitoring and detection refer to the activities involved in extracting information from the environment to check the state of the plant and determine whether it is operating correctly. An alarm system is an example of automation applied to monitoring and detection. Situation assessment is evaluating current conditions to assure their acceptability or determining the underlying causes of any abnormalities. An example of automation applied to situation assessment is a computerized operator-support system (COSS). Response planning refers to deciding upon a course of action to address the plant's current situation. In an NPP, procedures usually aid response planning. An example of automation applied to response planning is a computer-based procedure (CBP) system that accesses plant data and analyzes step logic to recommend a course of action to the operator. Response implementation is undertaking the actions specified by response planning. An example of automation applied to implementing a response is the issuance of sequential control commands using embedded soft controls. Finally, interface management encompasses activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen. An example of automating interface management is the automatic identification of a display appropriate to the current situation.

Processes of automation. Automation uses input from the plant (and perhaps the operator) and processes the information to accomplish a goal. These processes are an important aspect of automation in that they are the means by which automation performs its tasks. Automation processes can include control algorithms, decision logic (such as the use of Boolean logic), and virtually any other type of information processing routine suited to its tasks.

Modes of automation. Automated systems may have different modes of operation. Modes define sets of mutually exclusive behaviors that describe the relationship between input to the automation and the response to it (Jamieson & Vicente, 2005). A system can have multiple modes, but only one is active at a time. Modes do not imply differing levels of automation; rather, they involve performing the same function in different ways. Modes provide the capacity for a system to do different tasks, or to accomplish the same task using different strategies under changing conditions. A navigation device provides a simple example of modes. When a user inputs a destination, the device automatically plans the best route. Users can select driving- or the pedestrian-modes. In a city with one-way streets, the suggested route can be completely different depending on the mode selected. In driving mode, the one-way streets constrain the route selected; in the pedestrian mode, they do not constrain route selection. The task is the same, but its solution depends on the chosen mode. The Reactor Mode switch in a boiling water reactor similarly changes various automatic features.

Flexibility of allocation. A system can be designed such that the human or machine agent responsible for performing an activity is always the same, i.e., static allocation. Alternatively, a task can be performed either by automatic systems or by personnel based on situational considerations, such as the operator's overall workload. Some authors distinguish between adaptable automation and adaptive automation (Lee, 2006; Miller & Parasuraman, 2007). In the former, the operator selects the allocation and in the latter, the automation automatically adjusts based on some "triggering" conditions, such as an operator decision to change allocations, psycho-physiological measures, dynamic workload assessment, task-performance measures; and critical events or setpoints based on measured parameters (Prinzel, 2003).

Reliability of automation. The final dimension of automation is reliability. All engineered systems have less than perfect reliability. Automatic systems can fail in whole or in part and thus compromise their ability to achieve their intended function. When an automatic system has a simple, well-defined task to accomplish, its reliability is easy to quantify, e.g., as the probability the system will correctly perform its function. When its functions are complex, as is the case for many COSSs, defining the measures of reliability is more difficult. Further, it may be important to distinguish different aspects of an automatic system's functions. Thus, for an alarm system, reliability can be expressed in terms of misses (not alarming when alarm conditions exist) and false positives (alarming when an alarm condition does not exist). Further, automation's reliability may differ across different contexts of use, or modes of operation.

Conclusions. Our characterization of automation is generic; it defines the design envelope wherein any specific application of automation can be described. When applying dimensional characterizations to a specific application, they need to be interpreted with respect its specific functionality. That is, the generic characterization does not reflect the more fine-grained analysis that can be made after accounting for the specific functions of the automatic system being addressed, e.g., a decision aiding system vs. a control system.

General Principles for Supporting Human-Automation Interaction

We examined the effect of automation's design on human performance, linking the findings to the characterization dimensions as best we could. Our review was divided into the following topics:

- automation's reliability, operator trust, and the use of automation (e.g., Lee & See, 2004; Metzger & Parasuraman, 2005; Parasuraman & Riley, 1997)
- high-levels of automation and operator performance (e.g., Billings, 1977; Hollnagel, 1999; Funk & Lyall, 2000; Lee (2006); Parasuraman, Sheridan, & Wickens, 2000)
- intermediate- and low-levels of automation and operator performance (e.g., Kaber et al., 2001; Wright & Kaber, 2005; Land et al., 1995; Rook & McDonnell, 1993; Roth, Bennet, & Woods, 1987)
- varying levels of automation, adaptive automation, and operator performance (e.g., Cosenzo et al., 2008; Endsley, 1996; Kaber & Endsley, 2004; Lorenz et al., 2001; McGarry et al. 2005; Willems & Heiney , 2002)
- teamwork (e.g., Klein et al., 2004 & 2005; Lee & See, 2004; Parasuraman & Riley, 1997; Woods & Hollnagel, 2006)
- HSI design (e.g., Guerlain et al., 2002; Parasuraman et al., 1997, 2000)

Based on this literature, we derived several general principles for human-automation interaction:

Define the purpose of automation - Automation should have a clear purpose, meet an operational need, be well integrated into overall work practices, and be sufficiently flexible to handle anticipated situational variations and adapt to changing personnel needs.

Establish locus of authority - In general, personnel should be in charge of the automation, be able to redirect, be able to stop it, and assume control, if necessary. This does not preclude the automation from initiating actions. Some actions are allocated to automation because they cannot be reliably performed by personnel within time- or performance-requirements. There may be situations where automation initiates a critical action because personnel have failed to do so. Such automatically initiated actions, e.g., reactor SCRAM, are needed to support the safety of personnel and equipment.

Optimize the performance of human-machine team - The allocation of responsibilities between humans and machine agents should seek to optimize overall integrated team-performance. This may involve defining various levels of automation, each with clear-cut, specific responsibilities for all agents and each with a clear rationale. It also may involve flexible allocations that change in response to situational demands. Personnel's interactions with automation should support their development of a good understanding of the automation, and the maintenance of their personal skills needed to perform tasks if automation fails. This optimization may involve exposing personnel to various levels of automation. The HSIs should support a clear mutual understanding of the roles and responsibilities for both human and machine agents.

Understand the automation - Personnel should clearly understand the automation's abilities, limitations, and goals, and be able to predict its actions within its various contexts. Minimizing automation's complexity will support this objective. While operators' understanding largely will come from training and experience, the HSI should support that understanding by reinforcing the operator's appropriate mental model through the information provided in automation displays. That is, the HSI should portray an accurate representation of how the automation is functioning overall, and how it interacts with the plant functions, systems, and components.

Trust the automation - Personnel should have a well-calibrated trust in automation that involves knowing the situations when the automation can be relied on, which require increased oversight by personnel, and which are not appropriate for automation. The HSIs should support the calibration of trust, such as providing information about the automation's reliability in its various contexts of use and specific functions.

Maintain situation awareness - The HSIs to automation should provide sufficient information for personnel to monitor and maintain awareness of automation's goals, current status, progress, processes (logic/algorithms, reasoning bases), difficulties, and agent responsibilities. Attention should be given to changing the level of automation, and for flexibility where the roles and responsibilities of all agents may vary. HSIs should support differing information requirements, from determining the overall status- at-a-glance to more detailed data in support of greater interaction with automation.

*Support interaction and contro*l - Personnel interaction with automation should support the human's supervisory role:

- HSIs should support personnel interaction with automation at a level commensurate with the automation's characterization, e.g., level, function, and its reliability.
- Communication features should enable personnel to access additional information about automation's processes beyond that provided in monitoring displays. Automation should communicate with personnel when necessary, such as when it encounters an obstacle to meeting a goal, or when information is needed from personnel (e.g., information not accessible to automation). Communications from automation should be graded for importance, so as not to be overly intrusive.
- Personnel should be able to redirect automation to achieve operational goals, e.g., to override automation and assume manual control of all or part of the system.

Minimize workload from secondary tasks - A minimal workload should be entailed in dealing with the automation's configuration, and in monitoring, communicating, changing allocations, and directing it.

Manage failures - Automatic systems should support error tolerance and managing failures:

- Personnel should monitor the activities of automation to detect automation errors, and be adequately informed and knowledgeable to assume control if automation fails.
- Displays should support operators in determining the locus of failures as being either the automation or the systems with which the automation interfaces.
- To the extent possible, automation should monitor personnel activities to minimize human error by informing personnel of potential error-likely situations.
- Automation should degrade safely and straightforwardly when situations change sufficiently to render its performance unreliable, and should communicate this to personnel in a timely way to enable them to become more engaged in the responsibilities of the automation.

HSI Design Guidance

We used these general principles along with the technical basis derived from the literature to develop design review guidelines. The guidelines are organized into subsections, as shown in Figure 1. We documented the review guidance in the standard format of the NRC's HSI review guidance (O'Hara et al., 2002); an example is presented in Figure 2. In addition to the HSI review guidance, we provided insights into the design process, operator training, and operations.

HSIs for Automatic Systems

1 Automation Displays
  1.1 General Display Considerations
  1.2 Automation Representation
  1.3 Automation's Dynamic Status
2 Interaction and Control
3 Automation Modes
4 Automation Levels
  4.1 Shared Control
  4.2 Operation by Consent
  4.3 Operation by Exception
5 Adaptive Automation
6 Error Tolerance & Failure Management
7 HSI Integration

Figure 1 Organizational structure of HSI review guidance

8.1.2-1 Overall Representation of an Automation System
The HSI should accurately represent automation and its plant interfaces.
Additional Information: Providing a representation of the automation and the aspects of the plant with which it interfaces helps operators to link the actions of automation to its goals for the plant itself. For example, if automation is maintaining a level in a tank that has a leak, so long as automation can pump water in, the level is achieved and operators may not know there is a problem. When the level can no longer be maintained, operators need to quickly determine whether the failure is in the automation or the controlled system. Offering an overall representation of both automation and its plant interfaces helps operators assess this situation.

Figure 2 Format of an HFE design review guideline

DISCUSSION

Our review provided a considerable technical basis upon which to develop guidance for the interfaces with which operators can monitor and manage automation. During the course of our guidance development effort, we did identify several topics for which additional research is needed.

- Many of the studies we reviewed had limitations for generalizing the findings to the target operational context we are interested in: commercial nuclear power plants, highly trained professional operators, and complex HSIs. The findings of many of the studies we reviewed were based on students performing fairly simple tasks, using simple desktop HSIs. Research results are generalized most easily when the operational context is the same. Thus, research is needed to assess the extent to which generalization between these contexts is supported.
- Considerably less research has been conducted on HSI design for automatic systems than for many other aspects of human-automation interaction, such as trust and levels of automation. Further, the work that was done focused on very general characteristics of HSI design, rather than specific approaches. More research is needed on HSI design approaches to human-automation interactions.
- Levels and functions of automation often are confounded in the literature. Studies more specifically isolating the effects of each are required, so we can better understand the independent effects on the operator's performance of these two independent dimensions.

- We found that reliability effects operators' trust in automation and their decision to use it. Further, providing information about reliability in the HSI supports these decisions. But how reliability should be quantified and represented are not easy questions to answer, especially for automation supporting situation assessment and response planning. Additional research is needed.
- Automation's process can range from simple to complex. Research is needed to develop a better understanding of the relationship of its complexity and operator trust.
- Additional research is required to identify the appropriate triggering mechanisms for automation changes, and how they should be implemented to minimize any disruptions to the operator's performance when the change occurs.
- Finally, the technology of automation engendered a great deal of flexibility that affords operators many different types of involvement and interactions. Our characterization of automation revealed numerous dimensions, including levels, functions, flexibility (adaptive automation), and modes that can be combined to design a particular automation application. Yet designers lack methodologies to support decisions as to what combinations are appropriate. For example, current function-allocation methods do not address such decisions. Thus, additional research is needed on the "front-end" of an automation specification, that is, selecting what types of automation and what level of operator involvement to include.

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