A HUMAN AUTOMATION INTERACTION CONCEPT FOR A SMALL MODULAR REACTOR CONTROL ROOM

Katya Le Blanc*, Zach Spielman, and Rachael Hill
Idaho National Laboratory
*Katya.leblanc@inl.gov

Ross Snuggerud, Brandon Pearse, John McLerran, & Ryan Flamand
NuScale Power
6650 SW Redwood Lane Suite 210
Portland, OR 97224

ABSTRACT

Many advanced nuclear power plant (NPP) designs incorporate higher degrees of automation than the existing fleet of NPPs. Automation is being introduced or proposed in NPPs through a wide variety of systems and technologies, such as advanced displays, computer-based procedures, advanced alarm systems, and computerized operator support systems. Research consistently finds that there is a fundamental tradeoff between system performance with increased automation and reduced human performance. Idaho National Laboratory (INL) researchers and NuScale Power human factors and operations staff are working on a collaborative project to address the human performance challenges of increased automation and to determine the principles that lead to optimal performance in highly automated systems. This paper will describe this concept in detail and will describe an experimental test of the concept. The benefits and challenges of the approach will be discussed.

Key Words: Small Modular Reactors, Human System Interface, Automation, Situation Awareness

1 INTRODUCTION

Many advanced nuclear power plant (NPP) designs will utilize automation to a greater degree than the existing fleet of NPPs. Small modular Reactors (defined as reactors that have an output of 500 MWe or less), in particular will need higher levels of automation to support reduced staffing with the goal of minimizing Operations and Maintenance (O&M) costs. Although there is a wide breadth of research that investigates human-automation interaction, there are two critical gaps in the understanding of human automation interaction as it applies to the impact on human performance in complex safety-critical industries. The first is that most studies are conducted in laboratory environments with simplified tasks or in domains that may not translate well to nuclear power. The second gap is that research consistently finds that there is a fundamental tradeoff between system performance with increased automation and reduced human performance. There is little insight on how to increase automation without sacrificing human performance.

In highly automated systems the role of the human operator shifts from being a direct controller, to supervising automated activities. Reliable automation typically enhances overall performance of the human-machine system; however, it often also has the negative consequence of reducing human monitoring and situation awareness (SA). In systems where the human operator has the ultimate responsibility for maintaining a safe system state (such as NPPs), the operator must maintain a level of SA that will allow him/her to recover in case the automation fails or an unanticipated condition arises [1].

Automation is typically characterized based on how much in the system is automated and whether the automation is providing information gathering support, monitoring support, decision making support, or in carrying out control actions [2-3]. These two dimensions are often termed level of automation (i.e., how much is automated) and stage of automation (i.e., which human information processing stage is supported or replaced with automation). The existing taxonomies of automation typically characterize automation by listing the stages of automation and identifying which stages human operators are responsible for and which stages the automation are responsible for. Most human automation interaction research is conducted within the context of automation characterized using one of the existing taxonomies.

Generally, research has established that human SA is best under manual conditions (low levels of automation) and worst under conditions of high automation [1]. System performance tends to increase as level of automation increases, unless the automation fails or unanticipated conditions preclude the use of automation. The current literature identifies the negative consequences of automation and researchers have struggled to define how to enable high levels of automation without sacrificing human performance (i.e., SA and workload). The question of how to achieve the performance and efficiency gains of high levels of automation without also degrading human performance still remains unanswered.

Designers of new nuclear technologies recognize the many challenges with human-automation interaction in highly automated systems, and have identified this issue as an area that needs further investigation to ensure effective human-automation interaction. In order to address this challenge, Idaho National Laboratory (INL) and NuScale Power have partnered to design and evaluate new automation interaction concepts to ensure the design facilitates appropriate human situation awareness. The first phase of the collaborative research effort focused on the design of a human system interface for a highly automated task in a small modular reactor control room.

NuScale Power has a small modular reactor concept that utilizes up to 12 small integrated pressurized water reactors to provide a flexible nuclear generation facility. The NuScale Power design has many passive safety features that enable a simpler design compared to the existing fleet of large scale light water reactors. Further, in the NuScale Power concept each unit will produce about 50 MWe, which enables a modular design, but requires that the per-unit staffing be reduced compared to a traditional plant. Existing U.S., NRC staffing rules would require a minimum of 48 operators in the control for the 12-unit plant, which would not be sustainable from an O&M perspective. Hence, NuScale Power developed a concept of operation that utilizes the passive safety features and extensive automation to enable the control room for all 12 units to be safely staffed by 4 operators. These factors (among others) lead to the need for higher degrees of automation in the control room.

Boron dilution is an example of a task that will be partly automated in the NuScale Power control room, but still will involve human operator involvement in the decision making and monitoring. Boron dilutions are done over the course of an operating cycle for pressurized water reactors to maintain constant reactor power. As the nuclear fuel is depleted, it is necessary to provide positive reactivity additions to counter the reactivity loss due to the core depletion. The volume of boron free water (dilution water) needed to counter reactivity loss changes over core life. The boron concentration in the coolant lowers over core life, which requires an increase in the required dilution volume to achieve the same change in concentration. Early in life, the core will require around 10 gallons of dilution per day. Later in core life it can require thousands of gallons of dilution per day.

These dilutions are normally spread out over the course of the day to maintain the reactor operating at near peak efficiency. NuScale Power tentatively plans to spread out the boron dilutions to occur on a three to four hour frequency, which totals to roughly 8 - 10 dilutions per reactor per day. However, the nature of the NuScale Power reactor and the impact on the concept of operation may drive the number of dilutions per day to be reduced in the final operating plan.

In existing single unit pressure water reactors, the boron dilution activity is controlled by the operator who is queued to perform the task by some predetermined change in a key parameter, normally reactor coolant temperature. If NuScale Power were to implement this paradigm, the facility would need a dedicated operator to do nothing but perform dilutions all day.

To avoid this high operator burden, NuScale Power plans to raise the level of automation associated with the dilution process. Due to its importance to maintain expected plant performance, its potential consequences relative to reactivity control, and the more generic implication of automation in the NuScale Power design, the boron dilution activity was selected as initial the focus of the collaborative research effort. INL researchers and NuScale Power human factors and operations staff are collaborating to address the human performance challenges of increased automation and to determine the principles that lead to optimal performance in highly automated systems. The research team has developed a human-system interface design concept that facilities operator engagement of an automated process by providing "three-way communication" (analogous to the communication between crew members in an existing NPP) whereby control decisions are made collaboratively between the automation and the human. This paper will describe this concept in detail and will describe an experimental test of the concept.

2 DESIGN CONCEPT

Before designing the human system interface (HSI) for the boron dilution task, the researchers first identified the information requirements. The researchers walked through the task with operations, engineering, simulator, and human factors staff to identify what information operators need to make effective decisions during a dilution task and to identify where automation could optimally support operators. The researchers identified a set of primary information requirements that are directly related to conducting a dilution task and a set of secondary information requirements that support effective monitoring of dilution tasks.

The primary information sources help operators to determine the appropriate volume and rate of adding fresh water to the coolant system to conduct the dilution; they are directly related to the dilution task and should be reviewed and versified by the operator as part of the tasks. The secondary information sources support operators verifying that dilution is an appropriate action and support monitoring of the expected plant response. The third level of information is used to develop the interface with too much information; this information is tangentially related to the dilution task, but not necessary for verifying the parameters or follow-up monitoring.

Once the information requirements were validated with operations staff, the researchers designed three versions of the human system interface. In all three versions, the automation functioned similarly. It provided operators with suggested parameters for the dilutions (Volume and rate), allowed the operator to verify or change the suggested parameters, and then on operator command carried out the necessary actions to execute the dilution as specified. The three versions of the interface varied in the amount of supporting information presented to the operator through the dilution interface. Each of the interfaces is described in detail below.

2.1 Interface 1

The first interface provided the least amount of additional detail to the operator. The interface simply presented a mimic of the CVCS system, a mimic of the pressurizer, the delta T (difference between target T_{ave} and current T_{ave}), and the suggested rate and volume for the dilution (see Figure 1 for an illustration of the interface). Once the dilution is executed, the only monitoring support presented in the interface is a progress bar. This interface represents the minimum amount of information and interaction the operator needs to execute a dilution with automatic support.

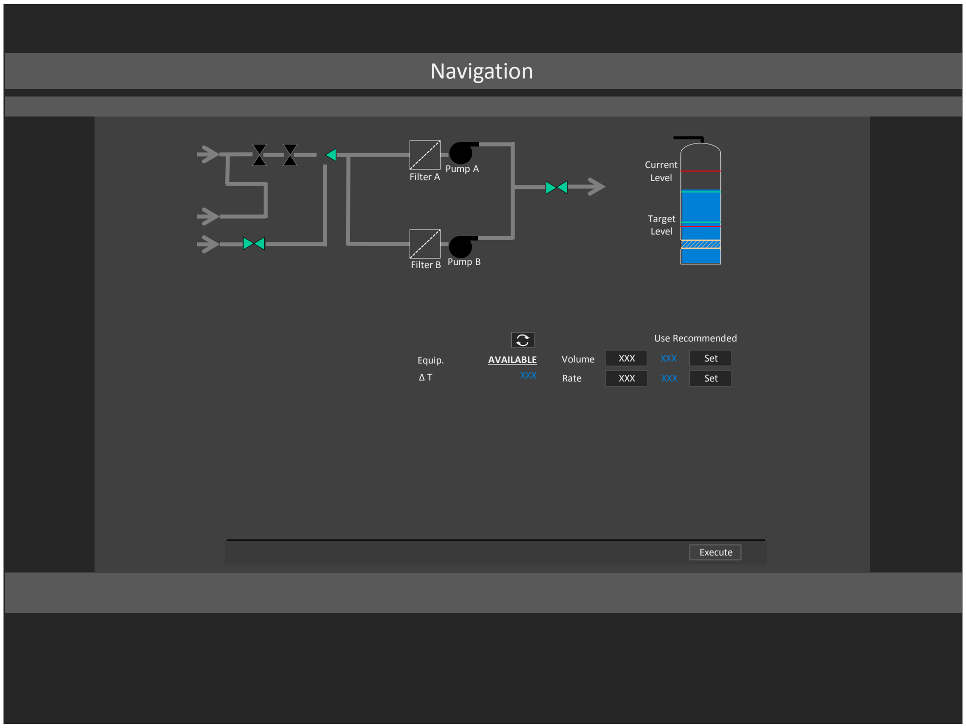

Figure 1. Interface 1 shows only suggested parameters without additional supporting information

2.2 Interface 2

The second interface (See Figure 2) provided what researchers hypothesized would be the optimal amount of information to support operator verification of automated suggestions and monitoring of plant response once the dilution is executed.

The design principles employed in this version are:

- Provide in the task interface all the information necessary to validate the automation's recommendations for the dilution under normal operating conditions, and highlight abnormal operating conditions when relevant along with providing link or access to additional relevant information
- Provide ONLY the information necessary to validate the recommendations and monitor the plant response
- Provide explicit descriptions of the expected plant response to facilitate the operator's review of the information before executing the dilution
- Provide feedback for operator input to ensure he is aware of any undesirable plant conditions that may arise from manually input parameters
- Provide context sensitive information by customizing the information so that it is relevant for the current phase of the task, such as verifying or inputting parameters for the dilution and monitoring once the dilution has been initiated

The interface provides the same mimics and automated suggestions for rate and volume of the dilution as in interface 1, but provides additional detail for the operator to verify the suggestions. The interface also provides a summary of the expected plant response to aid the operator in verifying the appropriateness of the automated suggestions or his manually input parameters. Under normal conditions, the operator would double check that the suggest rate and volume would produce a desirable plant response based on the predicted parameters displayed. If for some reason the operator needed to change the parameters from the “ideal” values suggested by the automation, the expected plant response would update, and the operator could verify that his input parameters would not result in an undesirable plant response Once the operator instructs the system to execute the actions, the interface would provide monitoring support by directly presenting the relevant plant parameters in addition to the progress bar. This interface is hypothesized to provide the operator with optimal detail to support effective interaction with automation and situation awareness. The interface provides context for the automatically suggested dilution parameters and additional information for continued monitoring of ongoing dilutions.

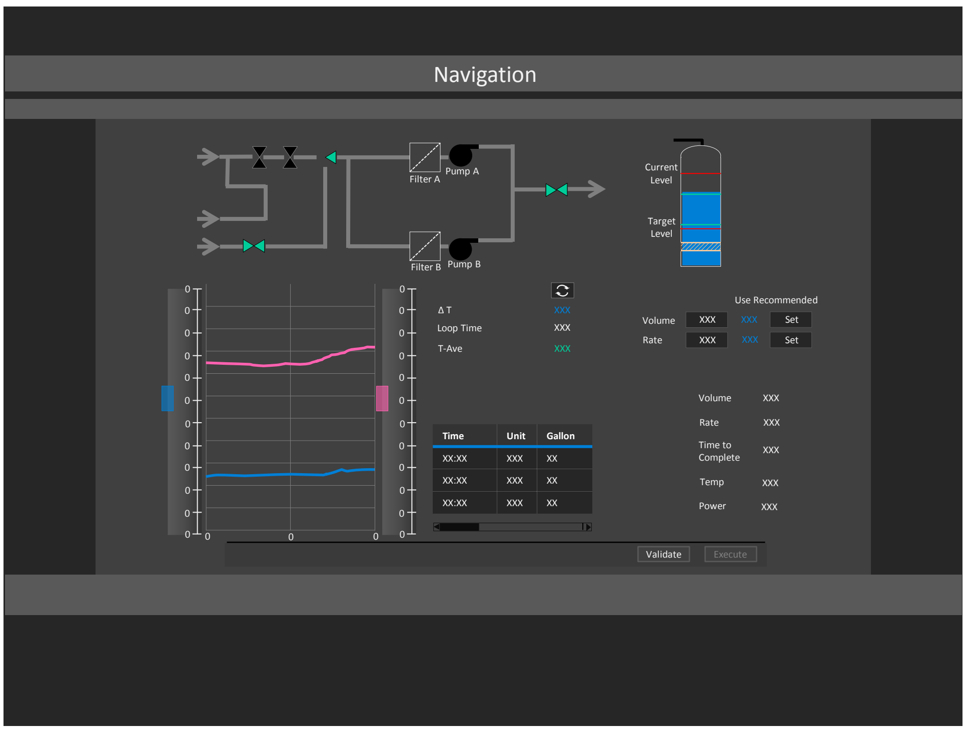

Figure 2. Interface 2 provides additional detail to support operator situation awareness.

2.3 Interface 3

The third interface (See Figure 3) is designed to investigate the effect of providing too much information to the operator. During the dilution tasks, the operator is still required to have high level awareness of the rest of the units. Drilling down into too much detail on a dilution task on a particular unit may reduce an operators overall situation awareness. It is tempting for designers to provide more information that is needed, especially in digital systems where a plethora of information is available. This interface has additional information that is only tangentially related to the dilution task and would only be needed in the most extraordinary of circumstances. Several additional parameters and longer history of past dilution are presented on this interface to test whether operators spend more time looking at unnecessary detail and unintentionally lose the big picture awareness of the entire plant.

3 EVALUATION OF HUMAN AUTOMATION INTERACTION

The researchers designed an experiment to test the dilution display's effect on performance, SA, and workload. The researchers worked closely with NuScale Power operations engineers, human factors engineers, and simulator engineers to design scenarios and performance measures for the experiment. The experiment will include 18 participants with operations experience and understanding the NuScale Power design who have been fully trained to operate the NuScale Power control room simulator. The results from the experiment will provide a basis for effective interface design to support human-automation interaction in highly automated contexts.

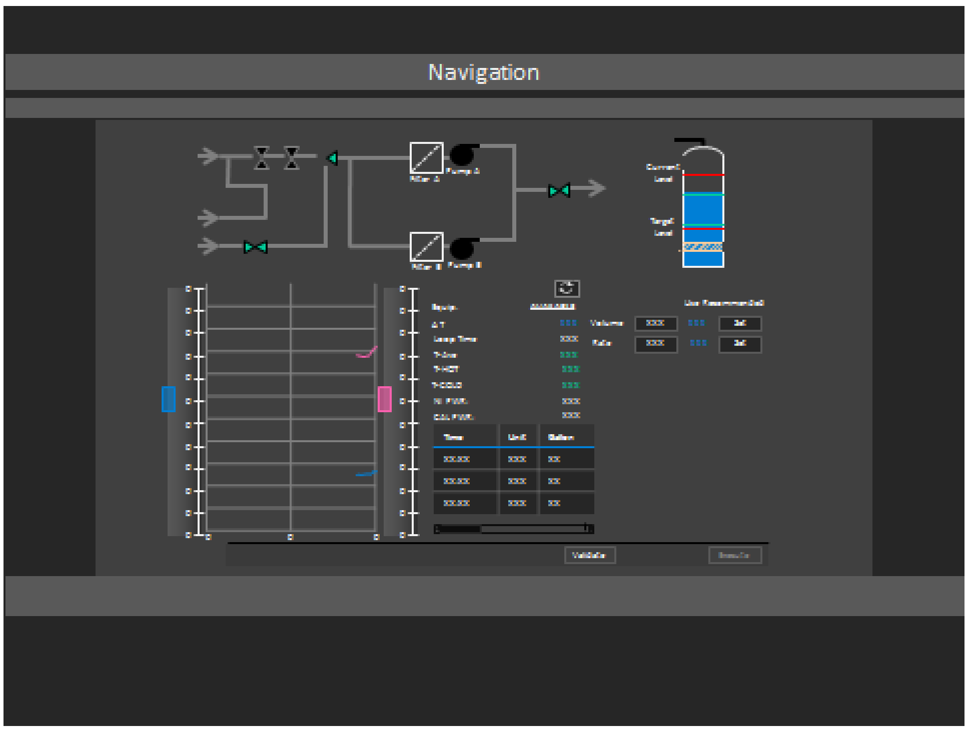

Figure 3. Interface 3 provides too much information to the operator.

4 CONCLUSION

The results of this research will inform effective principles for human-automation interaction that can apply to a variety of challenges facing industries that are designing and deploying advanced technologies with increased automation including SMRs. This work will also address some of the scientific challenges of assessing human behavior in high fidelity simulation environments by advancing methodology in the assessment of human performance. This study has been one of few to experimentally assess how a human system interface affects operator performance in full scale simulations with more than a few participants serving as crews.

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