The Optimized Design and Use of Automated Control Systems - State of the Literature and Proposed Research.

Joel M. Haight Ph.D., P.E.,
University of Pittsburgh
Dept. of Industrial Engineering
1043 Benedum Hall
Pittsburgh, PA 15301
jhaight@pitt.edu

Daniel G. Cole, Ph.D.
University of Pittsburgh
Dept. of Mechanical Engineering

Ervin Sejdic, Ph.D.
University of Pittsburgh
Dept. of Electrical and Computer Engineering

Abstract

Today we are faced with what some call the "automation paradox" and others call "the ironies of automation". Lisanne Bainbridge (1983) cautioned that the more automated a system becomes, the more important it is to appropriately integrate human contributions into the system. There is no question that automated control systems provide immeasurable benefit (improved efficiency, reliability, accuracy, safety, etc.); however, this comes at a cost; loss of skill, knowledge, decision-making capability and reaction-time in our human operators. Without daily engagement in the cognitive performance-based activities required by a control system, humans become less useful to the system. There seem to be two prevailing schools of thought on the best approach to human-system interface design. One advocates automating the system as much as possible to keep the human operator out of harm's way and to remove the error-prone human from critical operations. The other camp claims that the human operator suffers significant losses in physical capability, memory and attention capacity and their learned responses diminish in quality if they have not been actively and cognitively engaged in the operation. Then when called upon to take over control in an automated system, they are less capable of effectively operating the system manually. It is not well enough established which is correct or if there is a generalizable correct path.

Currently, as automated control systems are designed, it is often the case that operators are left in the operational fringes. So, researchers at the University of Pittsburgh have been exploring design methodologies that will allow system designers to understand and to then implement the best of the control system and human performance attributes, with the intent of concurrently minimizing the likelihood of human error-induced incidents. Through a series of trials using licensed reactor operators in a reconfigurable control room simulator, researchers are planning to identify and measure key performance variables while varying task configuration, level of automation, and override authority. If impact on system output is shown to be predictable, the generated model can help designers simulate various design strategies and their resulting impact on system performance, thus providing more-informed training protocols and content, more-informed simulator practice decisions and improved operational and operating procedure consistency.

Key words: Automated control systems, cognitive performance, human-machine interface

1. Introduction

It has long been known that if a human's cognitive input is not needed in a process for feedback interpretation, decision-making, action-taking or planning; they will disengage and focus on other parts of the operation or some other activity. In a sense, this can be a positive for the automated control system designer because he or she can free up the operator's attention capacity for other productive tasks such as future planning. However, this disengagement from the process can also lead to, as noted above, a loss of knowledge, loss of skills, memory decay, and possibly loss of attention capacity. (Haight, 2007) It could be referred to as sliding back down the learning curve. For airline pilots who have operated in the automated pilot world for many years, it was shown that many of these pilots were no longer as able to effectively carry out several types of interrupted landings as they once were. (Pasztor, 2013) Our retention of both knowledge and skills is related to how much we use them. We do not yet know if continued active operation alone is required or if some form or level of practice, training or reduced level of active operation can also achieve operator skill and knowledge retention targets while allowing the automated control system to operate the process optimally. It is also not known in the case of nuclear power plant and oil and gas production and processing operators, what specific activities and what level of engagement in those activities leads to optimum system performance. Does this include automation supervision? Does it include knowledge of and comfort with over-ride capability? Can it include intermittent but regular system checks with subsequent recording of meaningful system outputs? These are questions currently being explored at the University of Pittsburgh. Previous research has shown that experienced operators are much more inclined to want to operate more effectively in a less automated environment, while system designers seem to favor more automation. (Haight and Caringi, 2007) The debate and the research continue.

Like most complex systems and situations in this life, the best answer is not so black and white to be best addressed by one school of thought or the other. The best answer is probably something in between those two positions and it would be different for every system, task and situation. So if the answer is a mix between automated control and human input and since automated control system use is increasing in both numbers of operating systems and in complexity and capability, we must ask, in our design process, how much of the automated system function should we allocate to the human operator and how much autonomy and override capability are necessary to maintain safe and efficient operations. A nuclear industry goal is to maintain a high level of situational awareness and thus, promote improved decision-making quality. However, since we do not yet know if continued active engagement alone is necessary to avoid loss of human performance that can come from over-automation or if some lesser level of active engagement in the form of practice or training, as one might achieve in a simulator, is enough to maintain operator skill and knowledge retention targets as well as to maintain operating production levels and high quality standards. This remains to be explored.

Currently, as automated control systems are designed, it is often the case that operators are left in the operational fringes. So, researchers at the University of Pittsburgh have been exploring design methodologies that will allow system designers to understand and to then implement the best of the control system and human performance attributes, with the intent of concurrently minimizing the likelihood of human error-induced incidents. Through a series of trials using licensed reactor operators in a reconfigurable control room simulator, researchers are planning to identify and measure key performance variables while varying task configuration, level of automation, and override authority. If impact on system output is shown to be predictable, the generated model can help designers simulate various design strategies and their resulting impact on system performance, thus providing more-informed training protocols and content, more-informed simulator practice decisions and improved operational and operating procedure consistency.

It is well known that the information processing that one goes through in the operation of a complex system and for problem-solving in that complex process is effortful. This activity takes command of a significant percentage of one’s attention capacity. If effective reallocation of that cognitive load to the control system can be made, attention capacity is freed up to allow the operator to address other critical needs in the operation, such as needs that cannot be addressed by the automated control system. This could possibly be future operational planning or even anticipation of a near term, future state of the system, for example. (Sharples, Millen, Golightly and Balfe, 2011)

As noted above, a Wall Street journal article about a major Federal Aviation Administration report published in 2013 tells us that “commercial airline pilots have become so dependent on the automated control system on airplanes that poor manual flying skills and failure to master the latest changes in cockpit technology pose the greatest hazards to passengers…” Pasztor (author of the 2013 WSJ article) explains that the panel commissioning this study states that because pilots have become so used to the automated control that they have become reluctant to override the system. Over reliance on automation is a very real phenomenon and not only does it keep operators from realizing when they need to take over control, it is also responsible for the erosion of manual skills. It is reported that not only do operators lose confidence in their skills after a period of not using them; they also experience an actual and significant decline in those skills. The loss of both confidence and skill level can lead to poor or late decision-making. Devastating outcomes of these poor or late decisions can be also be realized in nuclear power plants, oil and gas refining and processing and any other process industry plants where catastrophic loss of containment of toxics, flammables, radioactive or reactive material is possible.

It is well established and agreed upon by the researchers at the University of Pittsburgh and industry people as a whole that automated control can help to ensure consistent and predictable performance of a reactor system or any other controlled complex system. However, while some adaptability can be designed into the control system, it lacks human-level flexibility and adaptability. It is not capable of supplying judgment to situations that were not programmed into its logic. While our human operators do bring judgment and adaptability to the system, we also introduce emotion, bias, fatigue, habits of mind and are generally unpredictable in nature and action. (Haight, 2007) In order to maximize overall system performance, one must design the control system by taking advantage of the strengths of the computer while concurrently taking full advantage of the experience, judgment, adaptability and intelligence of the human operator. In the experience of the authors, control system engineers seem to be more inclined to automate as much as possible and human operators, especially experienced ones are more inclined to want a predominantly manual system. How much do we involve the operators in the system operation? Do we only allow them to identify when the system is beginning to lose control and then give them the ability and the option to step in and take over the control? (Haight and Caringi, 2007)

The University of Pittsburgh research involves the development of analytical methodologies that will assist nuclear power plant control system engineers and designers in determining optimum levels of automation to design into their human-system interfaces to maximize overall operating performance. Researchers are attempting to highlight the means to maximize the performance attributes and qualities of the automation as well as those performance attributes and qualities of the human operator while concurrently identifying the means to minimize incident likelihood due to human error.

What is best for the nuclear power plant operator?

2. A practical determination

A case study was carried out during a project in which a control system for a batch chemical reactor was being considered for complete automation. As an indication of how these questions can be answered, a joint design team took on the designing the control system using a risk based analytical process. A modified failure modes effects and criticality analysis was used as an analytical method to help the team to determine the extent and level to which this system would be automated. The team was made up of the process engineer charged with accomplishing the design of the automation system, two operators, the operations manager, the engineering manager, an engineering researcher and a study coordinator. The 114 step batch recipe for a representative family of chemicals to be manufactured in this reactor was used as the design basis document. As each step of the batch procedure was analyzed for failure mode and/or successful dispatch, a determination was made as to whether the step should be automated, which should be maintained as manual and which would be a hybrid with some level of operator supervision. This determination was based on the probability of failure and the seriousness of the potential consequences of a failure in that step. While this was not a scientific means, the sound engineering judgment of an experienced team responsible for both the design and the operation was brought to bear. It was also a reasonable and practical approach to determining what was perceived to be the best function allocation based on the people who would be most responsible for using the system. The results of this analysis were a mix of relatively evenly distributed function allocations across automated, manual and partial automation with operator supervision. (Haight and Caringi, 2007) While no post-design or operational validation study was made of this system to determine that this mix was optimal, it is known that now nearly 8 years later, there has been no uncontrolled upsets in this reaction system. This concept can easily be applied in a nuclear power plant design project.

3. Adaptive Automation

As stated previously, it is important for nuclear power plant operators to maintain a high level of situational awareness, however, there is a bit of a fine line between and a competition with what it takes to maintain a high level of plant situational awareness and an exceedance of the workload limit that is required to attain and keep that situational awareness. (Kaber, Riley, Tan and Endsley, 2001) With the increase in the numbers and complexity of automated control systems, the well documented loss of task proficiency and reduced situational awareness certainly supports the movement to a design approach used in aviation called adaptive automation. (Bailey, Scerbo, Freeman, Mikulka and Scott, 2006) Bailey, et al. (2006) suggests that this adaptive automation where the level of automation or the number of systems under the control of the automated controller can be modified in real time as the system or the operator demands or needs. These systems can adjust their method of operation and can restructure a task depending upon how the task itself evolves and what the situation demands. Researchers in the past have argued that adaptive automation can reduce workload, enhance human performance and even improve the operators' situational awareness. (Bailey, et al., 2006) This approach to managing the apparent competition is directly applicable for use in nuclear power plant operation.

The concept in this approach is a dynamic allocation of control of a system's functions to the computer or to the human over time depending upon how well the human happens to be functioning or what her or his workload is. The allocations are based on the expectation that the goal is to optimize system performance. At times the operator may be functioning optimally and can handle the supervisory or other cognitive work load, but at a time when the operator is actively engaged in other activities, the controller can determine that the operator needs assistance and it can then allocate a particular function to the computer. (Kaber, Wright, Prinzel and Clamann, 2005) During complex operations, if operator sensory and psychomotor functions are being tracked, the system can use this information to estimate an overload point in the operator and can make the switch between computer operations and operator manual operations. The possible modes of operation under consideration here have to do with information acquisition, information analysis, decision making and action automation (the response to the process input). It is thought that this more user-centered design will alleviate "operator-being-out-of-the-loop type problems by keeping him or her in the loop, while still allowing the control system to continue to operate with the functions that it best manages. (Kaber, et al., 2001) Research has been done in the aviation industry, but while not much work has been done in the nuclear or process industries, the concepts can be considered for application there nonetheless. (Kaber, Wright, Prinzel and Clamann, 2005)

While either of these design approaches seem to have applicability in the nuclear power plant control system design, there is another approach that warrants consideration.

4. Flexible Interaction between Humans and Automation

Experienced researchers in the aviation control system design field propose that no system should be designed such that the automated control system has complete control and likewise, no control system should be designed such that the operator has complete manual control. These same researchers suggest that a concept of intermediate levels of automation be used as well as the implementation of a flexible allocation of control function be designed into the system such that, depending upon the status of the process, the work load of the operator or even the physiological and psychophysical state of the operator be accounted for in the allocation. (Miller and Parasuraman, 2007)

Miller and Parasuraman (2007) suggest consideration in the design for various levels of automation to be considered. This work and its consideration is discussed in the context of aviation, but these levels of automation can have direct application to nuclear and process industry control rooms. For example, these levels are:

"Full manual operation
Manual, but computer offers alternatives
Manual, but computer offers a prioritized or narrowed list of alternatives
Computer executes alternative if the human operator approves of the action.
Computer executes alternative, but the human operator can veto the alternative
Computer executes alternative and informs the human operator
Computer executes selected alternative and informs the human operator only if requested
Computer executes selected alternative and informs the human operator only if it decides to
Computer acts entirely autonomously"
(Miller and Parasuraman, 2007)

As the function allocation is determined, these or similar levels of automation are incorporated into the operation dynamically. In doing so, several researchers propose the concept of a "playbook" of a sports team as the approach to determine what "play" will be implemented in each particular situation, status or condition. Miller, Funk, Wu, Goldman, Meisner and Chapman (2005) suggest that as automation continues to become more sophisticated as each year arrives, the interface between the human operator and the control system becomes increasingly complex.

Miller, et al. (2005) propose that with this playbook style system, the human to machine delegation of function can be implemented similarly to any human to human delegation of a task or function. Care is needed in this case however, to ensure that the allocation is not just a transferring of workload where the operator's role and function is just transferred to the control system and the operator's role shifts to other activities that would allow him or her to disengage.

Miller et al. (2005) suggest that the key to this approach is to create automation that is smart enough such that instructing it is easy and that it maintain a subservient role in order to most appropriately implement all actions with the operator's intent. It is also critical that an established understanding between the operator and the automated control system be maintained…..what are the limits of the automation and the human operator….again, the operator does not just transfer a role to the automated control system unless the function of the system demands or requires it for effective process outcomes. It is an interesting concept that requires more research or at least exploration in nuclear power plant control room applications.

5. University of Pittsburgh Research Direction

From these studies, it is clear that the best solution for each system design is likely to be somewhere between full automation and fully manual operation. This is not a simple matter. The optimum location on the manual to automated continuum will be different for every system and even in every situation. It is therefore the goal of the University of Pittsburgh research to develop generalizable methodologies that will allow engineers to incorporate these adaptive and/or flexible design concepts in their control system designs that will help to ensure maximum system performance (efficiency, increased or stable production, reliability and achievement of consistent specifications) through optimizing the strengths and weaknesses of the computer and of the human operator.

This will be done by placing human operators in mock, but realistic, reconfigurable control rooms under various levels of automation to carry out common activities such as startup and shut down sequences. Researchers categorize and generalize the human actions necessary to carry out these tasks and the system responses that result during these series of tasks, using various levels of automation. The researchers then define, quantify and measure specific and appropriate human actions and physiological and cognitive responses during mock operation drills carried out in the reconfigurable control room as it relates and contributes to overall system performance. The emphasis of this research is on modernizations for legacy control rooms, and the measures produced are aimed at fulfilling the difficult licensing requirements for changes in crew control. The product of this research will be both a set of findings on the optimal level of automation as well as the scientific basis and measures for introducing automation into the control room. While the research is centered on legacy control rooms, the findings will readily inform new control room concepts such as small modular reactors.

Researchers will identify key performance variables and measure these variables and process system output variables while altering task configuration (e.g., normal events like start-up and shutdown transients, power change transients like daily load following, and abnormal events like reactor trips, turbine and generator trips, islanding, reactor coolant pump and feed-water pump trips, and accident scenarios like small and large break LOCAs, station blackout, and multiple system failures) and the level of automation incorporated. The study will introduce upset conditions into each sequence to determine the correctness of the human operator response, time to complete the response and error rates. These variables will be compared to system performance output variables.

Several scenarios, including normal and abnormal events, will be developed and each one will be implemented with different levels of automation along the manual-to-automated continuum. Once the control room simulator is programed with the sequences, operators will be asked to carry out each of the responses necessary to achieve successful completion of the sequence. The level of operator supervision that is required by each level of automation will be varied as will the amount of override capability in each sequence. (Tran, Boring, Dudenhoeffer, Hallbert, Keller, and Anderson, 2007)

As each operator carries out each sequence and deals with each upset, the researchers will assess multiple physiological systems. These recordings will also enable the researchers to track the interaction between multiple physiological systems during various operator sequences. Assessing interactions between multiple physiological systems will enable us to understand the fundamental causes leading to faults introduced by an operator (e.g., slowed respiratory and heart rates could denote that the operator is fatigued, which diminished her/his alertness). The operator errors will be tracked.

It is expected that these human performance variables will change in response to level of automation and to the significance and magnitude of the upset conditions that will be introduced mid-sequence. As the level of automation, supervision and override capability (input) are varied, the output variables will be determined. The measured internal human performance variables (output) will be documented (internal, heart rate, brain wave activity (both signal frequency and amplitude), etc.) as well as the external human performance variables – error (output) rates will be documented. These variables will be analyzed with the level of automation, level of overall task performance (success or failure), the level of system supervision required and the level of over-ride capability given. (Duschek and Schandry, 2007; Bay-Hansen, Ravn and Knudsen, 2003; Alexandrov, Sloan, Wong, Douville, Razumovsky, Koroshetz, Kaps and Tegeler, 2007)

It is then expected that the resulting mathematical relationship between input and output variables will be validated by implementation of model recommended automation strategies and subsequent measurement of error rates and overall system performance. Once the impact on human and system output show to be predictable via the simulation model, it can be used in real design applications by simulating various design strategies and their resulting impact on human and system performance with a more informed subsequent decision making on the appropriate design strategy. Another outcome will be that the operator’s changing role in the advancement of technology and the ever-increasing level of automation can be determined and predicted. This is expected to provide increased capability for and development of more informed training protocols and content, more informed decisions about simulator practice and improved consistency of operating procedures for the advanced technological equipment.

6. Final Thoughts

Everyone is different and every system is different. Each situation on each day can introduce differences. The complexity that results is significant and so designing a control system for a nuclear power plant that optimizes human and production performance every day and in every situation would be nearly impossible. However, it is a reasonable expectation that a flexible and adaptable system can be designed and employed in a nuclear power plant if it has the input of those that would design the system, those that would use the system and those who understand human performance and the limits and capacities of our human operators. Exciting improvements are coming.

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