The Design and Use of Automated Control Systems; where does the human operator optimally fit in? State of the Literature and Proposed Research

Joel M. Haight Ph.D., P.E.
Department of Industrial Engineering; University of Pittsburgh, Pittsburgh, PA 15261, U.S.A.

In today's technologically driven world, we face what has been called the “automation paradox”; Some have called it “the ironies of automation”. Lisanne Bainbridge (1983) cautioned us that the more automated a system becomes; the more important it is to consciously and appropriately integrate the human into the system. But what does “appropriately” mean? In general, it seems that the operating world does not question the fact that automated control systems provide immeasurable benefit (improved efficiency, reliability, accuracy, safety, etc.); however, it can be costly. We humans experience a loss of skill, knowledge, decision-making capability and reaction-time. Without frequent and active engagement in the cognitive performance-based activities required by a control system, humans become less to cope with, understand and function correctly in that control system. There seems to be two prevailing schools of thought on the best approach to the concept of automation. One of the two groups 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 group claims that the human operator suffers significant losses in physical capability, memory and attention capacity and, in addition, the quality of their learned responses diminishes significantly, if they have not been cognitively engaged in the operation. In this case, when called upon to take over control in an automated system, the operators are significantly less capable of effectively operating the system manually. It is not established which school of thought 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 and after thought and the design engineer leaves them in the operational fringes. So, researchers at the University of Pittsburgh are 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 nuclear power plant 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. It is expected that the results will be generalizable across all industry control systems. 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 is well-known that if a human's cognitive input is not used in operating a process for feedback interpretation, decision-making, action-taking or planning; they will disengage and focus their energies on other parts of the operation or worse, some other activity. This can be made to be a positive force for the automated control system designer because he or she, to a certain extent, can free the operator's attention capacity for other productive tasks such as the more cognitively complex concept or activity of future planning. However, when the operator disengages from the process, the phenomenon can also lead to, as noted above, a loss of knowledge, loss of skills, memory decay, and possibly loss of attention capacity. (Haight, 2007) For airline pilots who have operated in the automated pilot world for many
years, it was shown in a 2013 Wall Street Journal article by Pasztor 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) The operator, or in this case, the pilot, basically slides back down the learning curve. Our retention of both knowledge and skill is related to how much we use that knowledge and skill. We do not know if continued active operation alone is required or if some reduced level of operation supplemented with some form or level of practice, training can also achieve or maintain 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 the mining industry, nuclear power plant and oil and gas production and processing operators, in what specific activities operators must engage and if any engagement is necessary, what level of engagement in those activities leads to optimum system performance. Is supervision of the control system adequate? Does it require that the operator maintain over-ride capability? Is it adequate to include only 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 operate better and more effectively in a less automated environment, while system designers seem to favor more automation. (Haight and Caringi, 2007) The debate and the research must continue and it must include the mining community which is traditionally less automated. It is recognized that one major surface mining entity has moved towards automated haul trucks in some or all of their Australian mines.

Like most complex systems and situations, the best answer is not so black and white as 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 is likely to be different for every system, every task and every situation. So if the answer is a mix between automated control and manual human intervention 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 system function should we allocate to the 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. It is expected that this goal is common to the mining industry as well as to most industries. 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. We do not have proof that 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 levels as well as achieve the main goal of maintaining 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 are exploring design methodologies that will help control system design engineers to understand and to then integrate the best control system
and best human performance attributes. The intent is always to concurrently minimize the likelihood of human error-induced incidents while maximizing production output. Through a series of trials using licensed nuclear power plant reactor operators in a reconfigurable control room simulator, researchers are working to identify and measure key performance variables while varying task configuration, level of automation, and override authority. Part of the research plan involves determining the generalizability to other industries, especially, the mining industry. If impact on system output (in this case, megawatt production) is shown to be predictable, the generated mathematical model can then be used to 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.

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, especially needs that the automated system is not programmed to control. The operator could be free to address higher order thinking requirements, such as, future operational planning or even anticipation of a near term, future state of the system. (Sharples, Millen, Golightly and Balfe, 2011)

The Wall Street Journal article described above about a Federal Aviation Administration report published in 2013 explains that “commercial airline pilots have become so dependent on the automated control system that poor manual flying skills and failure to master the latest changes in cockpit technology pose a great risk to passengers...” Pasztor (2013) explained that the panel that commissioned this study found 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, automation-driven problem that not only keeps operators from realizing when they need to take over the control, it is also responsible for the erosion of manual skills. It is reported that not only do operators experience an actual and significant decline in their skills; they also lose confidence in their skills after a period of not using them. The loss of both confidence and skill level can lead to poor or the very least, late decision-making. Devastating outcomes of these kinds of decisions can be also be realized in mines, nuclear power plants, oil and gas refining and processing and any other industries where catastrophic loss of containment of toxics, flammables, radioactive or reactive material is possible.

It is agreed upon by the researchers at the University of Pittsburgh and has been suggested by industry people (the author was present during a speech as one mining company CEO explained that they are moving more towards automation and more towards “getting the operators out of harm’s way”. As a whole, the automated control can help to ensure consistent and predictable performance of a continuous
miner, a haul truck, a shuttle car or any other controlled complex system. The control system is not capable of supplying judgment to situations that were not programmed into its logic and human operators bring that judgment and adaptability to the system. However, there is a downside to human operators too. We introduce emotion, bias, fatigue, habits of mind (day dreaming) and are generally unpredictable in nature and action. (Haight, 2007) In order to maximize overall system performance, The design engineer must build the control system by building in the strengths of the computer while concurrently incorporating a way to integrate the experience, judgment, adaptability and intelligence of the human operator. What is the most optimum function allocation? Do we only allow operators 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? Or should this be the other way around? (Haight and Caringi, 2007) In fact, the expectation of the research at the University of Pittsburgh is to determine whether adaptive automation (the machine senses when the operator is overwhelmed or in the process of making a mistake and takes over control), which is becoming rapidly popular in some industries is the best approach.

The University of Pittsburgh research includes developing analytical methodologies that will assist control system engineers and designers in determining optimum levels of automation to maximize overall operating performance. Researchers are attempting to develop the methods 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.

2. A practical determination

The author conducted a case study during a project in which a control system for a batch chemical reactor was being considered for complete automation. In this study, a joint design team used a risk based analytical (modified failure modes effects and criticality analysis- FMECA) approach to determine the base function allocation of the reactor control system. 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. A 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, a determination was made as to the risk, convenience, and desirability of automating the step. It was also thoroughly considered to maintain manual mode or develop some type of integrated combination. 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 approach, the good sound engineering judgment of an experienced team responsible for both the design of the system studied and its operation was brought to bear and makes a strong case as a robust way to make this automation determination. 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, which included operator supervision. (Haight and Caringi, 2007) While no post-design or operational validation of this system was done to determine that the mix the team determined was optimal, it is known that nearly 9 years later, there have been no uncontrolled upsets in this reaction system. In the absence of more elaborate means, this approach can easily be applied to mining equipment design.

3. 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 mine equipment or mineral processing control room 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, (i.e., time of day, expected work load at specific times in the shift, etc.). (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 mining equipment and mineral processing control room as well as the nuclear, and process industry control room. For example, according to Miller and Parasuraman (2007), 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”

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

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 but that it maintains a subservient role in order to most appropriately implement all actions with the operator’s intent and not the programed control system’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 to free him or her from work load unless the function of the system demands or requires it for effective or efficient process outcomes. It is an interesting concept that requires more research or at least more exploration in mining equipment and mineral processing control room applications.

4. Adaptive Automation

It is important for miners, especially, large equipment operators, to maintain a high level of situational awareness. However, there is a fine line between what it takes to maintain a high level of situational awareness and an exceedance of the workload limit that is required to attain and keep that situational awareness. From a human factors engineering point of view, there is also a competition between these. (Kaber, Riley, Tan and Endsley, 2001) With the increase in the numbers and complexity of automated control systems, a loss of task proficiency and a reduced situational awareness are well documented and this supports the movement to a design approach as is used in aviation called adaptive automation. (Bailey, Scerbo, Freeman, Mikulka and Scott, 2007) Bailey, et al. (2007) 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., 2007) This approach to managing the apparent competition is directly applicable for use in mining operations. A recent example (14 May 2015) of this type of design is in the commuter train operations in Philadelphia, PA U.S.A. after a recent excess speed accident that killed several commuters, officials ensured the installation of a control system that warns the engineer that his or her speed is excessive in a specific speed limited zone and if the engineer does not respond within a few seconds, the system slows the train to the required speed limit.

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 allocation of function can go in both directions. If the control system doesn’t recognize a situation, the human is alerted and can take over control from the computer. 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) In the most elaborate of these systems, 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 and 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 mining, nuclear, or process industries, the concepts should be considered for application there nonetheless. (Kaber, Wright, Prinzel and Clamann, 2005)

While either of these design approaches seem to have applicability in the mining equipment control and the mineral process control room system design, there is another approach that warrants consideration.

5. University of Pittsburgh Research Direction

From these studies, it is clear that the best solution for each system design must be somewhere between full automation and fully manual operation. But, it is not as simple as that. The optimum location on the manual to automated continuum will be different for every system and for each and every situation. It is therefore the goal of the University of Pittsburgh research to develop generalizable methodologies that will allow engineers to incorporate these practical, 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 both the control system and of the human operator.

This is 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 modernization of legacy control rooms and for improved safety of equipment operators and control room operators. 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 mining equipment and into the mineral processing control room. While the research is centered on legacy control rooms, the findings will readily inform new mining equipment design applications.

Researchers 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 such as general equipment trips, turbine and generator trips, coolant pump and feed-water pump trips, and general accident scenarios, including multiple system failures) and the level of automation incorporated. The study introduces upset conditions into each sequence to determine the correctness of the human operator response, time to complete the response and error rates. These variables are compared to system performance output variables.

Several normal and abnormal event scenarios have been developed and will be implemented with varying levels of automation along the manual-to-automated continuum as defined by Miller and Parasuraman (2007). Once the control room simulator is programmed with the sequences, operators are 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 subject carries out the defined sequence and deals with each upset, researchers will assess multiple physiological systems. The results of these assessments will also enable the researchers to track any interactive effect between multiple physiological systems during various operator sequences. Assessing interactions between multiple physiological systems will enable the researchers to understand the fundamental causes leading to any errors introduced by the subject (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 hypothesized that the subject human performance variables will change in response to the level of automation introduced 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) are documented (internal, heart rate, brain wave activity (both signal frequency and amplitude),
galvanic skin conduction, transcranial Doppler blood flow, etc.) as well as the external human performance variables – error (output) rates will be documented. These variables will be analyzed against 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 any one day can introduce new differences. The complexity that results is significant and so the design of a control system for mining equipment and/or a mineral processing control room 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/or adaptable system can be designed and employed in these mining settings 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.

References


Bainbridge, L. 1983. Ironies of Automation, Automatica, 19, 775-779


