ENSURING OPERATOR RELIABILITY IN DIGITAL CONTROL ROOMS

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ABSTRACT

The U.S. fleet of nuclear power plants is aging, and efforts are being made to modernize instrumentation and control systems including integration of digital human-machine interfaces (HMIs) into the control room. Automation and control technologies have advanced since original systems were installed in the plants. This presents unique opportunities and challenges in ensuring the replacements are a benefit to the operators and the overall safe and reliable operation of the plant. We discuss trends we have observed from assisting utilities in their modernization efforts. Automation and evolving control rooms come with their own host of problems that existing human factors and engineering methods fail to capture. Traditional approaches are analytical approaches to ensuring reliability. Here we discuss some of the shortfalls of these traditional approaches as plants become increasingly more complex. We suggest that ensuring reliability for modernized and next generation control room will require expanding the scope of what was traditionally considered human factors as well as exploring novel approaches and methodologies for dealing with complexity and rapidly advancing technology.

Key Words: Human-Machine Interface, Human Factors, Human Reliability

1 INTRODUCTION

The United States' nuclear power production accounts for roughly 20% of the total country's energy production. The U.S. has a fleet of 99 operating reactors, each of which is a multi-billion dollar asset. Continuous improvements in technology and operation management have resulted in steadily increasing capacity factors across the industry. For these reasons, nuclear power will continue to play an essential role in the country's energy portfolio. The vast majority of U.S. power plants were designed, engineered, and built in the 1970s and 1980s. Over their operating lives, they have been continuously upgraded and improved upon as control and interface technology advanced.

Many plants are seeking license extensions to continue operating beyond their original 40-year licenses for another 20 or 40 years. In addition to modernizing components, plants are also investing in modifications to modernize instrumentation and control systems in their main control rooms.

1.1. Trend Towards Hybrid Control Rooms

Implementing fully digital control systems from top to bottom is both prohibitively expensive and technically unfeasible without disrupting plant outage cycles. The current, 'if it's not broken don't fix it' industry mentality also propounds it as unnecessary given that the safety systems have a proven track record of reliability. Plant modifications are being undertaken because business cases can justified on the basis that modifications can reduce operating costs and further increase plant capacity factors. In many plants sourcing replacement parts for original systems is growing more difficult and expensive by the day. Through modifications and upgrades, control rooms of Generation II power plants are trending towards analog/digital hybrids. Safety related controls will be maintained as-is while non-safety related analog instrumentation and controls will be removed to make room for digital displays to support digital human-machine interfaces (HMIs). By leaving existing safety related systems and controls plants can modernize without the burden of amending NRC operating licenses.

The fundamental layout of control rooms will likely remain unchanged. These plants contain vast networks of cabling that prevents drastic change to the footprint of the control room[1]. Operators will stand at the control boards, and for several reasons the existing operator roles will remain the same. New control technology offers enhanced automation capabilities compared to the existing largely analog systems installed in the plants. The goal is to take advantage of these increased capabilities to relieve operators from performing manual tasks requiring a high degree of attention. In other cases, the best option might be to replace functionality in-kind to avoid cascading consequences that would require significantly revamping how operations and maintenance is performed. Plants are upgrading control systems in a piecemeal fashion during scheduled outages. This also limits the extent to which operations can be modified as new control systems are put in place. For these reasons control room modernization presents unique challenges to operators, engineers, and human factors professionals.

These plants are not just technically complex. The plants are socio-technically complex. Much in the way that engineering psychology considers the human as part of the human-machine system a *socio-technical* system recognizes interactions between technological components and social elements like organizational culture and regulatory guidance. For the plant to function appropriately the technical and social components must work in concert. In contrast, next generation plants that are currently being commissioned can more easily take advantage of increased automation, computer-based procedures, and digital control systems from the outset. They do not have the physical control room constraints of current plants and can configure control rooms with large overview displays along the front with the operators stationed at desks facing towards the front. Each operator views an array of 4-6 displays as their window into the plant. New plants can also design socio-technical structures from the ground up without having to adapt to existing conventions. SMRs for example, are challenged because a team of operators may have to operate up to a dozen reactors simultaneously. With a conventional reactor three operators, a

[1] Plants contain miles of cabling with a good deal of it running to and from the control room. Some of the plants are old enough that they are beginning to examine how wire embrittlement will affect their long-term operations. For these reasons, it is preferred to leave as much of the existing wiring intact when performing upgrades. Because analog controls and indicators have dedicated runs to control equipment and field devices the available wiring behind the cabinet may even constrain were controls can be placed on modernized boards.

primary, secondary, and a senior operator, control a single reactor. When control systems are modernized, the existing procedures are amended based on discrepancies between the new and old systems. Despite the fact that control systems and interfaces are digital, the roles and interaction between human and machine are fundamentally unchanged. The capacity factor, profitability, and safety records of plants are a testament to the fact that they are already finely tuned socio-technical systems. Digitals systems may yield further optimization but it should be recognized they are not paradigm shifting in the manner that digital controls are for next generation control rooms.

1.2. Human Reliability, Performance, and Automation

Traditional safety engineering approaches are analytical. Systems are broken into sub-systems, and sub-systems are broken into components. We assume that by understanding the reliability of the components and the functional relationships between them we can assess the reliability of the system from the reliability of the components. As engineering psychologists, we are inclined to think of the humans as just another component in the human-machine system. When compared to manufactured components, humans may seem noisy, unpredictable, and unreliable. In fact, this may be more a reflection of the complexity of the human than a particular penchant for aleatory qualities within the species. The traditional safety engineering approach assumes safety can be achieved by making the components more reliable. For this reason, many engineers wish to design human operators out of the control system altogether. While it is true that there are many tasks that can be performed more reliably, precisely, and diligently by automation than humans, operators will continue to play a critical role in control systems despite their apparent overall low reliability compared to their electro-mechanical-silicon counterparts. Modern engineering is sufficient to ensure that a well specified, designed, validated, and verified system will function as intended for the known and considered circumstances. However, when the unexpected occurs the human components are what makes systems resilient. On September 11, 2001 in the midst of the tragic airline hijackings the FAA grounded all commercial flights. Air traffic controllers undertook the unprecedented task of safely, quickly, and efficiently landing over 5,000 commercial aircraft with over one million passengers in under two hours. The air traffic controllers had no procedures, protocols, or training for carrying out this feat. They had to not only land the planes, but maintain safe distances between them and identify other planes that were potentially under the control of hijackers. The intense communication and coordination between *human* pilots and *human* air traffic controllers allowed for clear skies after a chaotic stress-filled Tuesday morning. Much like the nuclear industry air traffic control has been subject to incremental technological advances, but the operating paradigm was largely unchanged from the 1960s [1].

Levenson suggests that the traditional engineering approach conflates reliability with safety. Safety is paramount, but reliability is not a guarantee of safety. Trouble can arise with systems that function reliably [2]. This could be due to peripheral cases that might have been overlooked or when a system has an unanticipated interaction with the larger socio-technical system. She gives the example of a chemical batch reactor accident that resulted in the release of the batch into the atmosphere. The chemical reactor had started a batch when a low oil reading caused the computer to annunciate an alarm and hold the system at a steady state. Under normal circumstances the reactor would increase cooling flow through a condenser to control the temperature of the reaction. Because the computer was programmed to hold the control variables at their current state the batch heated until a relief valve blew. The lesson here is that the controls acted as reliably and as specified. The failure was caused by an unforeseen interaction between components. Nuclear power plants are several orders of magnitude more complex than the chemical reactor in the example. With that level of complexity it is difficult to ensure all the possible interactions and points of failure have been taken into consideration. A system could also be functioning reliably yet be insecure and vulnerable to cyberattack. Even when security measures are in place, one must remember that bad agents are malicious, adaptive, deceptive, and intelligent which undermines traditional approaches of assessing failure [3]. It simply isn't possible to put a probability on the success of an attack that hasn't yet been implemented, that could potentially exploit unknown vulnerability of software systems or organizational protocols. Such risks fall into what Donald Rumsfeld termed 'unknown unknowns.'

In such cases, when the unexpected or the unanticipated events occur, it is the humans at the plant that provide resilience and maintain the safe operation of the system. Resilience is the ability of the system to return to an accepted level of operational normalcy in response to a disturbance. Rieger et al. [4] discuss how state awareness is essential to resilience. State awareness encompasses knowledge of the current operating state of the plant and knowledge of how control actions or changes to the system affect the operational state of the plant. State awareness can be built into technological systems, but must be implemented by defining explicit rules or through supervised learning. If the chemical batch reactor had state awareness it could have kept the coolant flow at a reduced level because the reactor would overheat. At this juncture we need to realize that machine intelligence In contrast, human intelligence is naturally inclined to possess state awareness and the necessary adaptability to understand and work through novel situations [4]. We should also keep in mind that while writing in some enhanced logic is wise and pertinent in many instances there are limits to how sophisticated we can make control systems in mission critical environments. Predicting every possible event and contingency is just not feasible or cost effective due to the complexity of the systems and constantly changing environments. Systems need to be adaptable and flexible while simultaneously being secure and robust to interaction faults. Increasing the sophistication of control systems non-linearly increases their commissioning cost and decreases their maintainability. More complex systems are inherently more difficult to maintain.

2. THE VISION

Over time as control systems become more sophisticated, the role of operators will evolve. Currently, plant evolutions require a dedicated operator or coordination between two or more operators to manually control one or more processes to move the plant to a desired state while maintaining critical plant variables within specified operating ranges. In these settings, a senior reactor operator delegates tasks to reactor operators so that they can maintain situational awareness of the plant as a whole. Future systems may be able to perform such evolutions in an autonomous manner and merely require operators to provide the requisite parameters and start a procedure while the control system itself would then perform the task [5].

Endsley has developed a level of automation (LOA) hierarchy with ten distinct levels [6]. The levels span from being fully manual to fully automated and are distinguished by who is monitoring, generating, selecting, and implementing the task. The automation described as Rigid System Level 7 is most akin to what is emerging in modernized control rooms. With Level 7 the human and machine are both responsible for monitoring the plant. The operators monitor primarily through analog and digital indicators.

The distributed control system monitors incoming sensor data and can be programmed to respond automatically if certain conditions are met. For example, if a turbine control system loses its speed indicators it will most likely trip the turbine. With a rigid system automation the machine generates the tasks that can be performed. This is a limited set of functionality that is dependent on the current state of the plant (mode dependent functionality). In this manner the automation restricts the operator from selecting actions that could damage the plant. For example, online control valve testing for a turbine control system may only be performed if the turbine is at less than a predetermined threshold load, otherwise the other control valves may not be able to compensate for the steam lost from the valve being tested. As already described, operators can choose from the available actions and the machine while carrying out the task. There are also cases where interlocks will take immediate action without consent from the operator to prevent equipment from becoming damaged or stressed or to prevent the system from falling into an abnormal state.

With envisioned systems the operator takes on a supervisory role ensuring the automation performs as expected. For the operator to perform this duty they must have a comprehensive understanding of the internal logic used by the control system. In the event that the control system fails, an operator is expected to possess sufficient skill to take over the task performed by the automation or to take appropriate action to ensure the plant does not end up in an adverse state.

3. REALITY

In the previous section we described a vision of how digital HMIs and automation should function in a modern control room. The picture that should be emerging is humans as integral components to complex evolving socio-technical systems driven by technological development. Plants are becoming more complex as digital control systems supplant or are layered on top of existing systems.

Technology has provided tangible benefits for process control. Digital systems provide better diagnostic capabilities in alarm management system, instrumentation is self-diagnosing and easier to connect without having to make dedicated wire runs, data historians provide data for engineers and operations management. But digitization, automation or computerization is a double edge sword (as described by Liu and Li [7]). Despite the control room vision previously described, operators are not trending towards Homer Simpson. In fact, the opposite is likely true, despite advances in digitization, automation, and control, operators need to know more than ever to effectively monitor the plant and determine if the plant is behaving abnormally. When the systems are simple there are fewer things that can break (even if they can break more frequently) and the plant as a whole is easier to understand. As digital control systems are adopted the intellectual manageability of plants decrease because there are more details to keep track and more ways that things can break. Plants as originally configured had near zero susceptibility to cyber-attack. Now all currently licensed plants must provide "high assurance that digital computer and communication systems and networks are adequately protected against cyber attack…" [8]. Counterintuitively, evidence suggests that increased automation may decrease human performance, because passive monitoring may decrease the operators situational awareness and degrade their ability to manually control the underlying plant processes [6].

3.1. It's Not the HMI, It's the Environment

In the early days of digital HMIs, Jens Rasmussen made the insight that semantics of digital interfaces was not the bottleneck for operators. Instead, the bottleneck was operators perceiving and understanding what the displays meant. Human factors engineers were treating the interfaces as the proximal target of the human interaction. Proximal analysis focuses on observable factors like whether the font is legible to operators, or whether they make the correct decisions merely through recognizing patterns between indicators or using heuristics to determine when to change a control.

These factors are important, but Rasmussen was trained as a control engineer and recognized that the interface is just a window to the plant, and the plant is the true target of the work. The goal of the interface is to allow the operators to understand what is happening behind the interface to provide resilience during anomalous circumstances. The traditional approach of determining whether the semantics of a widget were appropriately perceived and resulted in the correct action may be able to identify how reliable a human is when presented with certain stimuli, but it is insufficient to assess how that stimuli contributes to the operators' overall understanding of their environment. The former is a necessary condition for the latter, but the latter is becoming increasingly more important.

3.1.1 Human reliability versus human performance

More complex systems entail building more complex digital interfaces to allow operators to use the underlying functionality. Paradoxically, for human reliability assessment more complex and automated systems make humans less reliable when examining object level Human Error Probabilities (HEPs; errors per unit time for when interacting with particular objects like icons or buttons) [9]. Under the assumption that holistic task level reliability is the product of the required object interactions, one would assume that digital HMIs might operate worse and that holistic task level reliability would also decrease. This turns out to not be the case. Modern HMIs are tolerant to object level commission errors. They provide confirmation dialogs for engaging critical actions and, unlike their analog counterparts, will lock out control actions that should not be performed given the current state of the system.

The takeaway here is that human reliability and human performance are not synonymous. On screen (soft) keyboards that randomize their layouts every time they are opened have been found to be more reliable than their Qwerty counterparts. However, the input rate was 27% that of using a standard layout. As you might expect, users were also strongly dissatisfied with the randomized layout [10]. Available evidence suggests digital HMIs may make operators more error prone, but advanced control systems can compensate for these errors making the human machine system less likely to carry out unintended actions.

Another consideration is whether digital interfaces reduce operator workload (as intended) and improve task performance (prevent meaningful task errors). When a conventional control room was compared to a digital control room using full-scope simulators, the results suggest that the operators in digital control rooms experience higher complexity factors compared to conventional control rooms. Furthermore, abnormal and emergency situations were observed to exacerbate complexity factors [7].

3.1.2 Automation, workload, and performance

Wiener examined automated systems in the context of aviation and found tangible benefits to both task performance and operator workload when environmental complexity was low [11]. However, these results may not generalize to nuclear process control. A digital vs. conventional control room study found the digital increased subjective complexity even with scenarios depicting normal situations.

In more challenging circumstances, properly implemented automation may increase workload but also increase task performance [12], [6], and [13]. Monitoring automation requires understanding and predicting the behavior of the automation. If the plant changes in an unanticipated manner, the operator must reconcile what the automation is doing relative to their abstracted mental model of the system. Based on that determination they must decide when and how to intervene. Under time-critical dynamic conditions the cognitive effort needed to supervise automation can exceed the cognitive effort required to manually perform the task itself. If multiple systems in a plant are upgraded, then the burden for understanding the automation could be even greater due to coupling between the systems and the resulting interactions.

Hsieh et al. present a notable exception to the increased complexity resulting from automation in which they describe a decision support system for identifying abnormal operating procedures [14]. The decision support system helped operators determine the appropriate Emergency Operating Procedure, Abnormal Operating Procedure, or Annunciator Response Procedure out of a set of over 20,000 combined choices. When an event occurred the decision support system filtered out non-relevant procedures and rank-ordered the most relevant. The system decreased decision making time by 25% and increased accuracy by 18%. When two abnormal events occurred concurrently, the system improved accuracy by an even larger margin of 23%. The system also reduced subjective workload and was preferred by the majority of participants. From the operators' perspective, this technology simplified decision making by reducing the possible alternatives, prioritizing the remaining alternatives, and presenting them to operators. This reduces the operators' cognitive burden at the time at which it is in highest demand.

The flexibility of digital technology allows previously unprecedented amounts of data to be provided to operators. Once analog transmitters, indicators, and alarms are replaced with digital counterparts it becomes trivial to provide multiple threshold alarms, deviation alarms, and so forth. While this is possible it is not advisable, because not all of the data is informative to the operators [15]. On the interface front, Sarter and Woods discuss how there is a tendency to include more modes of operation than are strictly needed for the task [16]. Each additional mode requires the operator to understand when and how the mode should be used. Each additional mode also increases the propensity of mode errors where the operator thinks the system is in a mode that it isn't and performs an action that results in the process moving towards an undesired state. Additionally, some of the qualities of graceful degradation found in analog systems may not be replicated in digital systems, creating an all-or-nothing functionality that can paradoxically increase operational complexity for operators during fault conditions.

If you were to ask operators whether they would rather have the plants as they were originally configured or as configured now with plant process computers, digital controllers, and data historians, they would likely opt for plants as they exist now.

3.1.3 What about HMIs?

Digital HMIs are an inevitable destination on the roadmap of process control interfaces. Existing analog control systems are approaching obsolescence and are quickly becoming costly and time consuming to maintain. Integrated digital control solutions have been established in other domains for decades and have proven track records. From our discussion, it is clear that automation and digital HMIs need to be implemented with a great deal of care. As a design philosophy, we should return to Rasmussen's insight that the responsibility of operators is not to manipulate the interface but rather to control the plant. The HMI serves as the operators' window into the plant. The HMI needs to convey the indications and controls in a manner that is consistent with the operators' mental model of the plant. The goal is to provide feedback to the operators that allows them to determine what actions need to be taken to move the plant into the desired state based on first principles of understanding and prior familiarity with the plant. Yu et al. suggest an abstraction hierarchy that manages complexity by organizing systems hierarchically and depicting their structural relationships **[17]**.

Another important consideration for digital HMIs is understanding the context and uses of the HMI. When abnormal conditions arise, the thousands of pieces of information scattered across the display all compete for the operators' attention. The operator must rapidly assess and respond while also maintaining verbal communication with other operators. Any development of HMIs for process control, in particular nuclear power, should view operator attention as a valuable commodity that must be shared between numerous sources. Operators have procedures, but must be ready to operate several dozen sub systems and perform hundreds of procedures. To make matters worse there are numerous procedures that are only performed on an infrequent basis, perhaps once every outage. In such circumstances crews would likely receive just-in-time training to verify proficiency with the simulator before carrying out the procedure with the plant. Even so, this is a unique characteristic of process control that does not translate to other domains such as aviation. Routine tasks are performed on a much more frequent basis in aviation, which makes it easier for pilots to maintain competency between execution (by analogy imagine if pilots only really took off and landed a plane once every 24 months).

In the nuclear industry there is the lack of a clearly defined human factors process to follow to design, validate, evaluate, and verify digital HMIs. Most of the regulatory guidance is for physical indicators and controls **[18]**. Idaho National Laboratory has been working with utilities to perform formative design and evaluation using mockups and prototypes in a full-scope, full-scale simulator. The evaluation process uses licensed operators and other plant personnel to provide work domain context to the designers and control engineers contracted to carry-out upgrades. The framework has developed into the Guideline for Operational Nuclear Usability and Knowledge

Elicitation (GONUKE) and utilizes a knowledge elicitation process (epistemiation) that captures operator insights into the system **[19]**.

4. BEYOND THE INTERFACE

In summary, Nuclear power plants in the United States are modernizing control systems and interfaces that are approaching obsolesce and are difficult and costly to maintain. Modernization efforts can also increase the capacity factor of plants as well aid in the diagnosis and mitigation of abnormal events. Traditional human factors and engineering approaches have focused on reducing or preventing human error. New digital systems are more fault tolerate to operator error, but can also increase their cognitive burden because the resulting systems are technically more complex.

Human factors engineering must also evolve to address industry needs related to the modern era of digital control and advanced automation. The foundation of our domain is the bottom-up principles of psychology. We are less familiar with systems thinking, treating problems as holistic, and looking at problems from a top-down perspective. If we are interested in identifying and quantifying human behavior, then the bottom-up approach is well suited for developing a theoretical basis of the behavior. It provides the necessary control to systematically assess variation in response to stimuli in order to apply common statistical based psychological research methods. However, if we wish to extend that understanding to real world infrastructure, we need to move beyond the laboratory to more representational settings.

Also, if we wish to understand why accidents occur in the real world we need bear in mind that examining components in isolation eliminates interactions that may cause deleterious effects. Low-probability and high-consequence events rarely have a single cause of failure. Accident post-mortems often reveal a series of seemingly unrelated factors that on the surface seem independent of one another, but in conjunction result in catastrophe. Some of these factors can be technological, but they could also be regulatory, or related to the operational culture of the organization, the dynamics of the team, or the well-being of a single individual. Some factors are stochastic and completely out of our control like market factors, natural disasters and weather. If our goal is to enact improvements in safety and reliability, we need to chase the most meaningful factors, not necessarily the familiar factors. We won't solve these problems alone. As human factors practitioners, engineers, and academics our expertise lies in understanding the innumerable facets of human behavior and cognition. These include perception, memory, motor-coordination, and vigilance just to name a few. When viewed through the lens of engineering systems this expertise is required to understand systems in their entirety and to devise solutions that minimize unintended consequences.

Most of the user interface design occurs after the user and system requirements have been identified and the general architecture of the system has been decided. To even get to this stage a product must go through numerous reviews evaluating not only the technical feasibility but the business, lifecycle, and management feasibility as well. Projects that are not feasible, cost-justifiable, or able to garner management support fall by the way side leaving room for more viable contenders. Engineers of today must contend with numerous issues that were considered externalities by their predecessors. Modern technology and critical infrastructure have irrevocably shaped modern life by offering unprecedented convenience, comfort, and productivity. However, the global development and deployment of complex and interdependent systems has also resulted in unintended consequences. Most of the 21st century challenges involve fixing the successes of the greatest achievements of the 20th century because engineers failed to consider the social, environmental, and long-term societal impacts [20]. Human factors is needed at the formative stages of modernization to ensure the role of humans is appropriate and necessary.

DISCLAIMER

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