Nuclear Engineering and Technology 53 (2021) 3460–3463

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Human-machine system optimization in nuclear facility systems

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ARTICLE INFO

Article history:
Received 31 March 2021
Received in revised form
22 April 2021
Accepted 22 April 2021
Available online 30 April 2021

Keywords:
Human-machine interface
Human error
Human performance
System optimization
Nuclear safety
Automation

ABSTRACT

Present computing power and enhanced technology is progressing at a dramatic rate. These systems can unravel complex issues, assess and control processes, learn, and—in many cases—fully automate production. There is no doubt that technological advancement is improving many aspects of life, changing the landscape of virtually all industries and enhancing production beyond what was thought possible. However, the human is still a part of these systems. Consequently, as the advancement of systems transpires, the role of humans within those systems will unavoidably continue to adapt as well. Due to the human tendency for error, this technological advancement should compel a persistent emphasis on human error reduction as part of maximizing system efficiency and safety—especially in the context of the nuclear industry. Within this context, as new systems are designed and the role of the human is transformed, human error should be targeted for a significant decrease relative to predecessor systems and an equivalent increase in system stability and safety. This article contends that optimizing the roles of humans and machines in the design and implementation of new types of automation in nuclear facility systems should involve human error reduction without ignoring the essential importance of human interaction within those systems.

1. Introduction

There is evidence that those technological advances at a nuclear facility which affect the way operators interact within the system do increase the severity of human error-related incidents [1]. Consequently, the impact of human error on plant operations in relation to advanced technology integration is a subject worthy of exploration, especially in the context of new systems design [1,2].

Today's computing power and advancing technology is progressing at a dramatic rate. These user-friendly systems can unravel complex issues, assess and control processes, learn, and—in many cases—fully automate production. Although they do not think as humans do, they can imitate many human intellectual abilities. Throughout the last half-century, many industries have—for varying reasons—incorporated these technologies and removed the human operator from many aspects of operation [3].

Computers and automation are increasingly prevalent in many different kinds of knowledge work: pilots rely on computers to fly planes, doctors consult them in diagnosing illnesses, and architects use them to design buildings. However, this reliance on technology may come at a high price. Is our own understanding declining as we become more dependent on advancing technology and its broadening scale of influence?

One issue is that as technology continues to develop, the people using it have less opportunity to refine abilities on their own. A representative example is technology that offers too many prompts and tips to operators. By contrast, simpler, less helpful programs push operators to think harder, perform better, and learn more. Human skills are sharpened only through regular practice aimed at overcoming difficult and novel challenges [2].

Accordingly, as the development of new systems adapt to these advancing technologies, the role of humans within the functional architecture of those systems will inevitably continue to evolve as well. This evolution should necessitate an emphasis on human error reduction as part of maximizing system efficiency and safety—especially in the context of the nuclear industry. Within this context, as new systems are designed and the role of the human is adapted, human error should be pursued for a significant decrease relative to predecessor systems and an equivalent increase in system stability and safety. This paper presents considerations adapted specifically for the optimization of nuclear facilities that addresses the need for human error reduction without ignoring the essential importance of human interaction within those systems. Specifically discussed is 1) the understanding that human interaction is an inevitable attribute of a system, 2) the roles of complex

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https://doi.org/10.1016/j.net.2021.04.022

systems and human actors within the system, 3) the accounting for human limitations, and 4) the advised application of the dashboard concept in nuclear operation.

2. Considerations for optimization

2.1. Human interaction is inevitable

While it is reasonable to suppose that the best way to engineer fault-tolerant systems is to eliminate any potential for human error, this assumption can lead to the conclusion that everything should be automated provided that it can be automated. The flaw in this argument is that no matter how complex the system is, humans still need to interact with it. And when human interaction with a system is reduced, degradation of human skills can result.

For example, consider the decline in children's handwriting skills. In the past, all elementary students learned cursive writing. Today, the emphasis has shifted toward computers. As keyboarding skills have become more valued and children are spending less time on handwriting, there has been a corresponding decrease in this particular skill [4]. From a systems perspective, we can look at the Air Force as a model for addressing this kind of skill degradation. When pilots started flying jets with increasing degrees of automation, researchers found that while overall flying proficiency increased, pilots were losing their manual flight abilities [5]. As a result, pilot advisory boards recommended that pilots should increase manual flight hours to prevent losing those skills [2].

This issue can also be applied in the context of nuclear operations. For example, analog interfaces of predecessor systems typically compelled active engagement in the operation of the systems and equipment through manual log taking and parameter surveillance, as well as rudimentary comparison of the observed and logged values against system trends and acceptable operational parameters. This demanded active operator thought, engagement, and system adjustment to maintain systems in safe, optimal conditions. Newer nuclear systems, on the other hand, are comprised of digital displays with diverse, selectable views. These provide automated controlling functions which keep the operator passively informed without having to be an active participant in operation. This can lead to skill and system knowledge degradation, and when system upset conditions occur, the operator may be too far removed from the action to provide meaningful input and control.

For this purpose, the roles of humans and machines should be optimized in the design and implementation of new types of automation. But it must be understood that human interaction with systems is both inevitable and essential [3].

2.2. The roles of complex systems and human actors

From a systems design perspective, it is important to understand the precise role of complex systems in the interactions between human actors. In the past, computing and cybernetics systems were focused on extending the physical attributes of humans and doing things that humans could not safely do, such as interacting directly with highly radioactive materials. However, as computing power has increased consistent with Moore's Law, systems are now advancing into the realm of enhancing cognitive and mental capacities [5]. This makes reducing human error through system architecture a realizable and important goal, as can be illustrated by the case of tragic failures in the use of Patriot missiles in 2003 during the Iraq war.

The Patriot radar systems were engineered in such a way as to record false hits and false alarms without displaying any uncertainty regarding the target [6]. But the human tendency when working with such automated systems is to trust the accuracy of the information provided. As a result, when a British Tornado and a U.S. Navy F/A-18 were incorrectly identified as targets by the automated systems and subsequently shot down, the humans operating these systems received the blame [6]. This case illustrates that a crucial part of engineering human error out of systems designs is making certain that the systems do not introduce their own errors. If humans interacting with engineered solutions are to be expected to operate consistently, the systems must provide sufficient information so that operators can analyze each given situation and take the appropriate action. Therefore, a vital responsibility of the design engineer, when designing a human-machine interface system, is to properly articulate who makes the final judgement in crucial decisions.

In certain situations, automated systems should never be overridden by the human operator, such as if doing so would expose the humans involved to unacceptable amounts of radiation exposure, or automatic shutdowns due to low or high system pressure. On the other hand, there are situations—such as normal or controlled operations—when an automated system should not be able to override the operator's judgment. A good human-machine interface will achieve an appropriate balance between the skills of the operators and the inherent strengths of the systems involved in the given situation [2].

A lack of knowledge in the area of human cognition and cognitive processes is sometimes responsible for errors that occur in integration with automation systems. Humans have amazing but still limited cognitive abilities, and systems designers must take those limitations into consideration. For example, it is known that excessive use of multi-windowed systems for monitoring can result in degraded human performance, because these systems overtax the operator's attentional capacity [6]. Important alerts can be missed when human cognitive processing abilities are exceeded. Whereas an initial alarm can attract an operator's attention, repeated alarms (so-called “nuisance alarms”) inevitably desensitize the operator much like in the classic fable about crying wolf. In other words, when a truly important alarm is sounded, the operator may tune it out and not attend to it.

Excessive variety also presents a problem for human operators. A classic example is the smartphone: most users take advantage of only a small fraction of its functions, because most of them are too complex or take too much time to figure out. For systems designers to eliminate human error, they must compensate for this particular limitation by designing systems that augment the capacity for flexible thinking without overwhelming the user. An excessive variety of options means that crucial indicators or tools will be ignored rather than utilized by the humans for whom they are designed to assist [2].

The above issues should be addressed in the context of nuclear facilities. For example, nuclear operational displays should include uncluttered alarm pictures, in which overlapping information is excluded and alarm impacts are discriminated. System operational information should display all necessary system intelligence and control functions over non-safety systems. It can also be linked to the other controlling systems in order to automatically display related system information triggered by system alarms and programmed conditions. Additionally, these interfaces should continuously display safety system status and enable operators to control safety functions [7].

2.3. Accounting for human limitations

It is increasingly apparent that systems—unlike humans—have a nearly unlimited capacity. So, a respect for the limitations of the human brain and its processing capacity is necessary in order to create systems that reduce human error as much as possible. The area of the brain responsible for short-term memory is a major limiting factor [8]. The short-term memory circuit consists of sensory memory—which can contain a few seconds of data at most—and the short-term memory store. The complexity of designing with respect for this system lies in the fact that the attention capacities of short-term memory are divided between data just taken in, data retrieved from long-term memory for processing, coding procedures, and search strategies [8]. Therefore, when designing complex systems with many things that demand attention, systems designers should find a way to narrow the information presented to the most essential elements. This way, crucial information is front and center at all times [2].

For instance, consider the essential safety role played by visual control systems in automobiles. Indeed, the electronic instrument cluster is a crucial part of the safe operation of a motor vehicle because it relays safety-related signals to the driver [9]. There are many components designed to assist the driver by relaying such signals, including collision detection, parking assistance, night vision assistance, adaptive cruise control, and so on. But as automobile safety systems become increasingly advanced, the space available for displaying this information in the instrument cluster becomes a serious limitation [9].

To deal with this problem, designers have turned to the novel solution of creating configurable dashboards. Research on automobile interfaces has found that customizable dashboard interfaces increased passive safety, as the ability to configure the interfaces was correlated with significant improvements in users' attention and reaction capabilities [10]. One reason posited for this improvement in attention is that customized interfaces are closer to the real-world systems that they are supposed to support. Lim et al. [10] argue that this has to do with the end user being directly involved in the customization. A reduction of the psychological distance between the user and the system makes it easier for the user to execute the needed tasks [2]. A salient takeaway from this research is that additional information must be provided to the driver of the automobile without simultaneously distracting him or her from the primary goal, i.e., to safely operate the automobile. This clearly illustrates how human-machine interfaces in cars must be designed in a way such as to prevent human error [9].

This insight can be directly applied to the arrangement and composition of nuclear facility control interfaces. Vital operational information should be maintained at the forefront (such as reactor power, core temperature and pressure, etc.), but other information can be managed and displayed at the operator's discretion or according to plant procedures. This arrangement combines the availability of vital information with operator knowledge—based on training and experience—as to which displays are necessary at different times, all without overwhelming the operator's cognitive capacity [2].

2.4. Application of the dashboard concept in nuclear operations

Considerable data suggest that the concept of a "dashboard" holds promise in the area of human-machine interface design. One of the most valuable aspects of dashboards is that they can improve decision making (or prevent errors) by amplifying cognition as well as making the most of limited perceptual capacity [11]. According to Lim et al. [10], flexibility in selection of dashboard formats aids in user response and accuracy in using information. Additionally, dashboards can be an effective solution to the problem of memory overload—a key limiting factor contributing to human error in human-machine interfaces [2].

Several elements of dashboard design should be taken into account when one is designing human-machine interfaces. The first factor is visualization. The information visualized within a dashboard design should actually amplify cognition. The visualization of data can be considered correct if the end users consistently properly decode the information presented. Again, with respect to the limited cognitive capacity of short-term or processing memory, an effective dashboard design will strike an appropriate balance between visual complexity and the information utility required for the particular situation [2].

Other functions can be built into dashboards to reduce errors. For example, automated alerts (in limited amounts so as to avoid the aforementioned problem of desensitization) can be included in the dashboard design, along with theory-guided format selections that can help lead an operator to the correct selections for a given scenario. Limiting the dashboard to a single page and a simple color scheme, along with links and grid lines for 2D/3D data graphs, is another research-supported way to improve the visual clarity of dashboard designs [11].

Another important aspect of human-machine interface design is the affordance of information in a way that is consistent with the desired results. In this context, "affordance" refers to the features provided to the user [12]. One way in which affordance can reduce human error is in the proper presentation of choices or options. For example, shading a button or menu item in gray and making that choice inaccessible in order to indicate its inappropriateness can guide the user toward making correct choices in the situation. There is, however, an accompanying danger such that affordances can misinform or misdirect a user into an incorrect choice or option. For example, a horizontal line on a scrolling page could lead the user into thinking that the page has ended when actually there is more content "below the fold." Improper or misunderstood instructions can introduce or increase the opportunity for human error in human-machine interface use [2].

3. Conclusion

As the nuclear industry evolves, the technologically advanced systems and plants of the nuclear fleet need to emphasize a continuous effort to keep human error as low as possible. Systems technology will continue to advance, and the function of the humans within the system must continue to adjust as well. This state of affairs compels the steady progress of human error reduction without compromising system efficiency and safety. As novel future systems are designed and the function of the human is modified, human error should be engineered for significant reduction in contrast to predecessor systems, with a corresponding amplification in system stability and safety. This calls for a refined focus appropriate for an innovative suite of nuclear facility technology, including new automation types and roles for humans adapted in order to accommodate. As this paper has discussed, this new focus should stimulate the optimization of human-machine roles to decrease human error and increase essential stability of the system [2,3] via the appreciation that human interaction is an inevitable attribute of a system, understanding the roles of complex systems and human actors within the systems, awareness of and accounting for human limitations, and the advised application of the dashboard concept in nuclear operation.

As new systems are designed, design teams should view the system with an open mind, give consideration to the various technology options, account for human limitations, and—ultimately—establish appropriate requirements for the system and for the human in a synchronized, ameliorated approach. The amalgamation of these elements will suitably balance the next-generation system and lead to an optimized human-machine system [2,3].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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