Automated Control Systems

Do they reduce human error and incidents?

By Joel M. Haight

WITH EACH PASSING DAY, the world becomes more technologically advanced. As automation, artificial intelligence and robotics improve, it may be increasingly tempting to employ automatic means to accomplish production goals. Just think of it: If no humans were on the production floor, no more human errors would occur, no one would get injured, and companies would produce higher-quality product that they could move faster to market. Supervisors would not have to deal with employees who arrive late, get tired, want time off, complain about conditions, get hurt, spoil batches and generally disrupt operations.

The ability to move higher-quality product out the door faster would seem enough for any company to want to automate every process. In fact, trends suggest this may be happening. Management consultant Walter Bennis says that the factory of the future will have only two employees, a human and a dog—with the human there only to feed the dog and the dog there to bite the human if s/he touches anything (Paradies & Unger, 2000).

Few would argue that automated control systems are not necessary in today's complex industrial processes. However, is complete automation the best or most appropriate approach? While control system automation provides predictable, consistent performance, it lacks human judgment, adaptability and logic. Conversely, humans provide judgment, adaptability, experience and sound logic, yet are unpredictable, unreliable, inconsistent, subject to emotions and alternative motivations, and not biomechanically efficient.

This raises two important questions: 1) To maximize system performance, should we automate humans out of the system? or 2) Do we maximize human input and lose efficient, consistent, error-free system performance? The answer is that the proper level of automation is likely somewhere between these two extremes and it is likely different for each system and situation (Haight & Kecojevic, 2005).

Joel M. Haight, Ph.D., P.E., CSP, CIH, *is an associate professor in Penn State University's Department of Energy and Geo-Environmental Engineering. He is also the program chair for the industrial health and safety degree program. Haight holds an M.S. and a Ph.D. in Industrial and System Engineering, both from Auburn University. Before joining the Penn State faculty, Haight was an engineer and manager for Chevron Corp. He is a professional member of ASSE and Administrator of the Society's Engineering Practice Specialty. He is also a member of AIHA and the Human Factors and Ergonomics Society.*

This article reviews existing literature on automated control systems and human interface, and attempts to extend the work of Haight and Kecojevic (2005). The goal is to develop a method that helps design engineers determine how to minimize human error while maximizing system performance and better understand the right human/machine mix (Haight & Kecojevic, 2005).

The Problem

Does automation of control systems in industry really increase system productivity and help to reduce human error? Intuitively, most would believe that if humans were engineered out of the system, productivity would increase and errors would decrease. So, it may follow that industry is moving toward more automation—particularly since human error is inevitable and because humans fatigue easily and have short attention spans and memories.

However, while it may be appealing to automate systems, humans provide judgment, logic, experience and opinions (Haight & Kecojevic, 2005). Another concern is that in seeking to increase the level of automation, one promotes the likelihood of human operators switching to "habits of mind" (Louis & Sutton, 1991). This promotes a phenomenon called overreliance.

Designers, engineers, researchers and practitioners need to understand the human as a component in the system—and as one that is interactive, variable and adaptable. This adaptability and the ability to specialize responses to the situation mean that humans can play many roles and address many system needs. However, problems arise when

Abstract: *To maximize system performance, should we automate humans out of the system or do we maximize human input and possibly lose efficient, consistent, error-free system performance? The answer is likely in the middle of these two extremes. It is also likely to be different for each individual system and situation. This article outlines a method that design engineers can use to determine how to minimize human error while maximizing system performance and better understand the right human/machine mix.*

this natural human variability makes it possible for the operator to take actions that are not tolerable by the system (Haight & Kecojevic, 2005; Lorenzo, 1990).

Each year, industries experience many incidents (e.g., injuries, fires, spills, unplanned equipment downtime) and human error is often implicated as a causal or contributing factor. But this raises a paradox: Automating a process can reduce human error, and the level of automation in industry appears to be increasing rapidly. One would expect fewer incidents, yet industrial injuries do not seem to be decreasing. While it would be a stretch to suggest that industry has initiated a coordinated effort to reduce injuries by automating processes, it seems reasonable to expect that the number of injuries would decrease noticeably during this period of increased automation.

However, it may be difficult to reach an irrefutable conclusion on this until research is conducted specifically to compare, over time, the number of automation-error-induced injuries to the level of automation. That said, SH&E professionals and related disciplines can at least work toward an understanding of how humans and control systems interface in order to maximize the strengths—and minimize the weaknesses—of each. Since it can be reasonably well argued that a large percentage of industrial incidents are contributed to or caused by human error, SH&E professionals must explore the ways that automated control systems can help to reduce errors and error-induced incidents.

Human & Machine Strengths & Weaknesses

The need for efficient, productive output has helped drive the increase in automated control systems. However, this growth has come at a cost.

> Twenty-two years ago, this author, while learning oil production operations, spent much time in the field with experienced first-line supervisors. It was impressive to watch them in action. A supervisor would stop the truck upon hearing something out of the ordinary (a hiss, an unfamiliar vibration). He would listen more closely; place his hand on a pump or piping, then radio maintenance to request the repair of a leak, a bad order bearing or some other problem (Haight & Kecojevic, 2005).

Supervisors and operators of that era (now 25 years ago) relied on sentient knowledge, which is gained from the senses and through experience (the concept of "gut feel" is involved) to accomplish work objectives. They could tell how the process was running by sight, sound and smell. They had a "feel" for the system. While they did not have a quantitative feel for the process, and although this

Table 1

Human vs. Machine Strengths & Weaknesses

Human component		Automated control system	
Strengths	**Weaknesses**	**Strengths**	**Weaknesses**
Judgment	Inconsistent	Consistent	Lacks judgment
Adaptable	Vision, hearing, reach, strength, attention span limited	Predictable	Cannot be programmed for all eventualities
Sentient knowledge	Unpredictable, possibly unreliable	Efficient	Lacks sentient knowledge
Interactive	Subject to emotion, bias, alternative motivations	Uniform, reliable	Constrained by human limitations in design, installation, use
Can use experience	Forgetful, subject to distractions	Fatigue-resistant	Subject to wear and tear
Can learn, adapt	Subject to fatigue	No attention span limits	Adapted responses must be programmed—human programmers

Note. *Adapted from “Automation vs. Human Intervention—What Is the Best Fit for the Optimal System Performance?” by J.M. Haight and V. Kecojevic, 2005,* Process Safety Progress Journal, 24, *pp. 45-51.*

sense is not adequate to fully achieve system objectives, it is generally recognized that to have this feel for the system is a positive aspect of a person’s experience level. As industry and businesses rely more on computer-controlled automation, it is less likely that operators will develop this feel (Haight & Kecojevic, 2005).

Thus, to maximize system or production performance, engineers must properly consider the strengths and weaknesses of both the control system and the human operator. Since this is difficult for any one person, control system engineers must work with human factors engineers and system operators to design a control system—and each must take the others’ objectives into account.

As noted, humans bring with them judgment, flexibility, adaptability, experience and sentient knowledge. Humans also have physical, cognitive and emotional capacities and limitations that cause humans to be unpredictable, unreliable, biomechanically inefficient, subject to distraction and easily fatigued. Control systems have none of these limitations, yet they do not provide the human strengths of judgment, experience and adapted responses. Table 1 presents a comparison of these attributes.

Why Automate?

Safety

It is an oversimplification to state that fewer humans involved results in a safer system. However, it can be said that when a process is operated in a consistent, reliable, predictable, stable manner as facilitated by an automated control system, humans are better able to keep up with what is happening in the system. It frees their attention, leaves them less fatigued, enables them to think as opposed to act, and makes them less likely to rush through decisions and responses. This logic supports the move toward increased automation. Thus, even though economics has been a primary driving force in the increase in automation, it could be argued that automation provides a higher level of system safety (Haight & Kecojevic, 2005).

Efficiency, Speed, Reliability, Consistency

It has been established in the literature that automated control systems perform a function more efficiently, reliably and accurately than a human operator. It has also been proposed that these systems perform a function at a lower cost than the operator can (Parasuraman & Riley, 1997). Haight and Kecojevic (2005) summarize much of the existing literature by suggesting that automated control systems are installed to relieve human operators of time-consuming and labor-intensive tasks; increase the speed of an operation and production rates; extend shift operations or change to continuous production; increase system efficiency; or ensure that consistent, predictable physical specifications are maintained and consistent. Automated systems also free the operator’s attention capacity and time to allow the opportunity for long-range planning or more complex decision making (Kirlik, 1993).

Few would argue about the benefits of automation or with the trend toward more automation. However, complete automation is rarely the best approach; humans must be appropriately integrated into the automation. The decision to automate is like any other design decision in which competing objectives and system performance optimization are present and necessary. As noted, an automated control system must be designed properly, with appropriate understanding of and consideration for the strengths and weaknesses of both humans and the control system.

Why Are Humans Necessary?

What role should humans play in modern production systems? Humans are a critical component thanks to their flexibility, adaptability and creativity, and because they are better able to respond to changes or unforeseen conditions (Parasuraman & Riley, 1997).

Therefore, in modern process operations, an adapted response often is required. Because of control system limitations, humans do not always see a complete process parameter status when they need to, so they are forced to rely on factors such as experience, extrapolation and alternative signals to achieve systems objectives (Jamieson & Vicente, 2005). Humans provide intelligence, planning, creative thinking and decision making, and other higher cognitive functions. These are supervisory functions, a role that is likely most appropriate role for humans.

However, it is difficult for the design engineer to know what level of supervisory responsibility is required or best (Kirlik, 1993). The challenge is to integrate the best human qualities into the system without bypassing the benefits of automation. This is not always achieved, which can lead to problems. System override capability is another important issue the designer must address in terms of where to apply it and to what extent. System override capability in the hands of an untrained operator can be disastrous.

Automated Systems: What Can Go Wrong?

One accepted definition of human error is, "A human action that consists of any significant deviation from a previously established, required or expected standard of human performance" (Petersen, 1996; Peters, 1966). When the operator errs and causes a system to fail, the system usually does not fail due to any one reason (Petersen, 1996)—the problem is not solely the automation or only the operator. A system fails for many reasons, such as human/machine interface design decisions, operator qualifications and experience, the amount of training received, and the level to which operators are physically or mentally able to cope with the system and its changes (Haight & Kecojevic, 2005). A system can fail due to errors made as a result of problems in operating procedures as well (Chapanis, 1972).

It is also important to recognize that most human errors do not occur because the individual involved is wrong or not intelligent (Petersen, 1996). People make errors because, in the moment, they make decisions and take actions that seem logical given the situations and systems in which they are operating. In essence, errors are "caused" (Petersen, 1996). Human actions are taken based on, among other things, information provided by the automated control system (Haight & Kecojevic, 2005).

Many system failures also can be traced to problems with operator trust in the automation (Lee & See, 2004) and whether an operator overrelies or underrelies on the automation as a result. This trust can be partially rooted in the amount and accuracy of the feedback the operator receives from the control system. The operator must trust that the system is accurate, functional, reliable and consistent, or s/he will not trust the automation (Kirlik, 1993). When this occurs, the operator may circumvent or disable the automation and rely on manual input, thus losing any safety or error-reducing benefits of the automation (Molloy & Parasuraman, 1996).

For example, if a high temperature alarm/controller is subject to frequent spurious trips and false alarms, operators learn to disconnect the alarm, acknowledge it and not respond, or switch to manual operation and risk not recognizing the need to quench a runaway reaction. Human operators are even more likely to distrust and underrely on an automated system if its performance on "easy" tasks or tasks the operators believe they can perform themselves is unreliable (Madhavan, Wiegmann & Lacson, 2006).

The opposite is problematic as well. If the system minimizes the need for human input and is accurate and reliable, the operator may switch to "habits of mind" and overrely on the automation (Parasuraman & Riley, 1997; Louis & Sutton, 1991). The operator then allocates no attention to the system, believing the automation will "take care of everything." This phenomenon is illustrated in the *Far Side* comic that shows two airline pilots peering through the opening in the clouds at a mountain goat standing in front of them while they wonder (out loud, it is presumed) what a mountain goat could be doing all the way up there in that cloud bank (Haight & Kecojevic, 2005; Larson, 1986).

Human Roles in Automated System

- Acknowledge only, control system signals (do not make a change to the process).
- Acknowledge control system signals (make required physical system changes).
- Record data and communicate results to supervisor or to an electronic system.
- Manually note instrument readings and adjust process as needed.
- Monitor system status and override specific controls if it becomes necessary.
- Monitor system status and only report findings while making no change to the system.

Note. *Adapted from "Automation vs. Human Intervention—What Is the Best Fit for the Optimal System Performance?" by J.M. Haight and V. Kecojevic, 2005,* Process Safety Progress Journal, 24.

There must be a healthy level of questioning of the system without distrust to achieve desired system performance, and operators must remain engaged in the system's operation. The level of trust that humans have in a system and the role that it plays is crucial. Human interaction with automated control systems is probably most influenced by this factor (Sheridan & Ferrell, 1974).

An operator can be cognitively engaged in order to receive accurate and understandable feedback about system status and mode. If the operator understands the system's operating mode and status, s/he is in a better position to respond to upset conditions (Mumaw, Roth, Vicente et al., 2000; Jamieson & Vicente, 2005). This feedback must be provided in a timely manner and not in quantities that would overwhelm the operator. If system feedback is not provided or is not provided fast enough for the operator to respond appropriately, then the operator must play catch up; this breeds errors, which produce unplanned upsets, injuries or other failures.

Because of underreliance or overreliance on automation, distrust or inadequate feedback, operators may misuse the automated components they are operating (Parasuraman & Riley, 1997). Misuse also can be characterized as underreliance or overreliance

Care must be taken to ensure that the expected engagement is real and necessary. Humans learn quickly whether their actions are necessary, valued or integral to the process.

on the automated components. An example of underreliance would be an operator disconnecting an engine's over-speed governor or trip mechanism to avoid an alarm condition. An example of overreliance would be an operator allowing a reliable level control system to shut off flow to a vessel so s/he can perform other tasks even when the job requires 100% attendance. If the level system fails, the vessel will be overfilled, resulting in a spill. Engineers and operators must strive, through discussion and teamwork, to minimize or design these problems out of the system (Haight & Kecojevic, 2005).

The loss of an operator's "feel" for the process is another concern (Haight & Kecojevic, 2005). Operators who cannot sense that something is wrong in the system must rely on the automation to catch a problem. Without the sentient knowledge one develops from living with the system and its problems, the risk of human error or incident is higher. In addition, the more automated a system becomes, the more reliant an operator may become. This can cause the operator to stay in the habits-of-mind mode where s/he is less likely to detect a problem when the control system fails (Louis & Sutton, 1991).

Integrating the Human into the System

Automated control systems are designed by humans, so they are subject to human errors and limitations in and of themselves. It is nearly impossible to design a system to appropriately respond to every conceivable configuration of an event or combination of events in a production cycle. So, the engineer must integrate the human operator into the design process so that s/he can provide the judgment and flexibility necessary to formulate and implement adapted responses as unforeseen events occur.

This is no easy task. Humans are driven by ambition and emotion, and are subject to attention lapses, inconsistencies and forgetfulness. People allow their cognitive functions to disengage—often without realizing it. People switch between habits of mind (think autopilot) and active thinking several times each day. Periods of daydreaming are common as well.

It is not easy to determine what triggers and motivates the switch (Louis & Sutton, 1991). It is believed that the more humans remain actively engaged in the process, the more likely they will remain in active thinking mode. Therefore, system designers should strive to design a system which integrates the operator in such a way that s/he remains in active thinking mode (Haight & Kecojevic, 2005).

To maximize system performance, the literature emphasizes the need to take advantage of the human and control system strengths, then to create effective and active communication between them (Degani & Heymann, 2002). The sidebar on p. 23 ("Human Roles") shows the possible roles the human operator can fill that require communication with the control system.

The design of automated control systems is a complex process that has countless variables. To describe this, it is appropriate to start with a definition for automation. One accepted definition is the execution by a machine agent (usually a computer) of a function that was previously performed by a human (Parasuraman & Riley, 1997). In most cases, however, automation is not intended to completely remove the human; rather, to maximize the strengths of an automated control system, automation changes the role of the operator to that of overseer or human/machine interface manager (Parasuraman & Riley, 1997; Kirlik, 1993).

Problems arise when a designer does not consider all possible ways in which the human role can be changed or when unintended or unanticipated system or human responses result. Since it is nearly impossible for a designer to factor in all potential responses, it appears that an optimized system that maximizes performance and minimizes human errors will dynamically operate somewhere between full automation and complete manual control depending on the application (Haight & Kecojevic, 2005). Since integration system decisions must be based on the application, a generic design model would be a helpful tool for engineers. While no one such "tool" exists, several partial models and a solid level of understanding of human/machine interface can be effectively used.

To minimize human error, a designer must integrate human input in such a way that the operator stays mentally and physically engaged in the system's operation. The literature suggests consideration for models such as "adaptive automation" in which humans are expected to remain part of the monitoring system and remain engaged and adaptive to changes in the information being processed by the system (Kaber, Wright, Prinzel et al., 2005). Other research suggests consideration for systems that require human operators to be cognizant of the system's operating mode and to be engaged particularly during mode transition (Jamieson & Vicente, 2005).

An important consideration is how much override ability an operator should have. Ideally, as an interface "manager," the operator should have a monitoring role with complete override capabilities; should receive adequate system status feedback with enough time to respond; and should trust system accuracy and reliability (Sklar & Sarter, 1999; Reising & Sanderson, 2004).

This is difficult to achieve, however, and is made more complex by the phenomenon in which the level of interaction between the operator and the control system changes and develops over time. As training and experience change, so will the input from the operator. An experienced, well-trained operator can become bored and less vigilant over time as the challenge of learning a new system decreases. This can lead to more errors and it is not fully in the control of the system designer (Haight & Kecojevic, 2005)

A bigger challenge is to understand how the human operator works—with respect to factors such as physical, mental, motivational and emotional aspects, training level and experience. Often, a system is automated for economic reasons, leaving the human operator to manage an unwieldy system as best as possible (Parasuraman & Riley, 1997). This forces the operator to respond to an action already taken by the system on the system's terms. As a result, the operator is always playing catch-up and is less able to anticipate and avoid problems (Parasuraman & Riley, 1997).

Clearly, the design engineer must account for a complex set of variables in considering what function the operator will provide, then allocate the functions accordingly between operator and machine (Waterson, Older Gray & Clegg, 2002). Function allocation decisions are design-based decisions. Unfortunately, when designers allocate system functions such that an operator has override capabilities with too much room for discretion, without adequate feedback about system status soon enough to allow the operator to take action, a problem leading to an error, an incident or both is more likely (Haight & Kecojevic, 2005). If function allocation is to be a successful, the system must provide adequate, appropriate and timely feedback when necessary (Sklar & Sarter, 1999).

Several approaches can keep operators engaged. For example, an operator may be required to manually record data during the process or may be expected to analyze or trend process data. However, care must be taken to ensure that the expected engagement is real and necessary. Humans learn quickly whether their actions are important, necessary, valued or integral to the process.

To keep an operator mentally engaged and to be successful in achieving design objectives, the designer must consider issues such as performance feedback, the level of training and experience, and the speed at which the operator must respond (Prinzel, Freeman, Scerbo et al., 2003; Sklar & Sarter, 1999). Several accidents illustrate that design engineers have yet to achieve human and automation integration to the necessary level. Airplanes operating on automatic pilot being flown into terrain and railcars operating without speed constraints being derailed show that problems still exist (Parasuraman & Riley, 1997). To overcome this disconnect, designers should always work closely with those who will be using their designs (Haight & Kecojevic 2005).

Human performance variables—such as adaptability, judgment, future-planning ability and creativity—must be quantified and integrated into a design as well. The full potential and benefit of an automated system cannot be achieved if the human operator makes an error that shuts down the system.

To facilitate this integration, dynamic task allocation is another tool the designer can consider. This is required in the design of complex systems because no one design fits all systems. It is the cognitive human factors version of the adjustable-height worktable (Waterson, Older Gray & Clegg, 2002). In this system, dynamic and variable levels of task allocation between operator and machine are allowed. Design and operation decision making is back in the hands of the human, so training, experience, bias and related factors must be considered when determining who will operate the system. This creates additional challenges since the engineer has little input on personnel selection.

System operators have been known to circumvent automated components of a system (Kirlik, 1993). It may be that operators believe the system hinders their work or is time-consuming. Perhaps the system is known to malfunction. Whatever the cause, when this occurs, the operators may no longer be engaged—physically or mentally—and it is likely they would not follow an operation closely (Prinzel, Freeman, Scerbo et al., 2003).

Given this dilemma, the level of automation for an operating system must be appropriate and properly designed. This depends on the operators for whom the system is being designed. This is also out of the designer's control and may be dependent on factors such as operator age, training level and technological savvy.

To address this issue, the designer has several considerations. Successfully accounting for these variables can result in higher productivity and fewer errors ("Automation Level" sidebar above). A traditional approach to automating a system involves the operator's ability to manually switch to either full manual control or to the machine having full control at any one time (Parasuraman & Riley, 1997; Fitts, 1951). In today's systems, functions can be performed adequately by either the human operator or the automated system, but most systems function so that the attention (in various forms) of both is required at the same time.

This requires task allocation decisions to be made with input from system operators (Parasuraman, Mouloua & Molloy, 1996). The system designer must determine for each function or task to be performed whether the human or the automated system or both should have system control. The designer must also decide whether the operator should be given per-

Automation Level Design Questions

- How easy is the system to use?
- What is the type of automation and what feedback does it provide the operator?
- How frequent and how perceptible is the operational feedback?
- What is the level to which the operator is kept mentally or physically engaged in system operation?
- How easy is it to switch from automatic to manual control?
- How reliable is the system?

Note. *Adapted from "Automation vs. Human Intervention—What Is the Best Fit for the Optimal System Performance?" by J.M. Haight and V. Kecojevic, 2005,* Process Safety Progress Journal, 24.

Automation vs. Manual Control Design Decisions

Step in Batch Process

Two hours after starting the pre-emulsion step, increase the agitation rate to 40 rpm. When preparation step is complete, charge 240 gallons of deionized (DI) water to reactor holding tank.

Automation Control Concerns

Control system is more effective in keeping track of the 2-hour time requirement and can more effectively monitor and maintain 40 rpm.

Two types of water are connected to the reactor system. If programmed, the automated control valve will open only the correct valve to introduce DI water. 240 gallons is accurately measured based on flow rate measurement. If flow measurement is off, valve will remain open as long as flow control allows it to remain—too much water can be added.

Manual Control Concerns

Operator must determine when pre-emulsion step is complete and set the 2-hour clock. Operator must monitor agitation rate to ensure no foaming.

Water cannot efficiently be manually weighed up or measured and then carried to the reactor manually.

Design Decision Made

Appropriate to automate, but since only the operator can determine when pre-emulsion step is complete and whether there is foaming at 40 rpm, the operator must closely supervise the operation and have 100% override. Each step must be signed off on batch card.

Automate the system to operate the feed valve when DI water (only) is required. Tie flow measurement to feed valve to ensure that it closes when 240 gallons have been introduced.

Reasoning for Decision

This step requires operator judgment and experience. While the automation can be set for 2 hours and 40 rpm, the human operator must make decisions as the process is carried out.

Too much water and the recipe is prone to foam. Too little water and the material will remain a darker color and batch quality will suffer. Darker color can only be determined by experienced operator, so again, operator supervision is appropriate with 100% override capability if foaming or dark color result.

mission to switch easily between automatic and manual control; whether the operator should be able to override automatic control; and how the operator will be notified that a mode switch is required (Haight & Kecojevic, 2005).

Communication (feedback) and coordination between operator and system is critical in situations where they share control, such as in pharmaceutical process operations (Degani & Heymann, 2002). If the operator cannot tell easily when a change is required or that the system is no longer functioning, problems arise and errors are made (Haight & Kecojevic, 2005). In a cardiac hospital, when a heart rate or blood pressure sensor becomes disengaged without a feedback signal going to the monitoring technician, no treatment steps can be taken; the patient can die if an adverse condition goes unheeded. In such cases, it is acceptable to switch between automatic control and manual control, but the operators must be made aware that the switch is necessary or has already occurred.

Clearly, a design engineer has much to consider—much more than is even discussed here. Furthermore, many variables are associated with each consideration (Parasuraman, Mouloua & Molloy, 1996). More research is needed to develop an improved design model that can be used generically to fit all situations in order to help process-plant control-system designers make the appropriate design/integration decisions.

Mathematical Modeling

Most design processes involve competing objectives. To address these, the engineer must rely on the practice of optimization of design variables. To do this, the engineer must first develop and quantify system performance variables. While this is not new science, it is often difficult to quantify human performance variables such as motivation, training, emotion, judgment, flexibility, adaptability, fatigue or boredom. Thus, an engineer must use some type of comparative index that has no true quantitative meaning but does have comparative value. It is then necessary to somehow rank these difficult-to-quantify variables for use in the objective function of an optimization equation.

Engineers must also account for the operator's trust in the system in terms of designing the system for maximum reliability (Kirlik, 1993). More research is needed to fine-tune this quantification process. A rough optimization function must then be built based on the mathematical relationship between these variables and final system performance. A generalized optimization function model may follow this format (adapted from Haight & Kecojevic, 2005).

Equation 1

$$\text{Max. } Y = A_1 + A_2 \ldots A_n + H_1 + H_2 + \ldots H_n$$

$$\text{S.T.} \quad Y > 0$$

$$\text{Min. } E = X_1H_1 + X_2H_2 + \ldots X_nH_n$$

$$\text{S.T.} \quad E \geq 0$$

Where Y is overall system performance
A is the automation variables
H is the human variables
X is error rates for human performance variables
E is errors

System modeling using operations research is not new, but a challenge still remains. It is difficult to define the right variables and quantify them appropriately in a human-based model. This is undeveloped territory and so far involves subjective considerations. More research is needed so that system designers, operators and human factors engineers study jointly the human/machine interface in automated control systems (Haight & Kecojevic, 2005).

An Applied Example

A batch chemical process considering a redesign of a reactor system to full automation recently undertook a needs analysis and an evaluation of where the automation versus manual integration needed. The author led a team through a human reliability analysis and discussion in which each step in a representative batch process was considered for automation. The team was made up of two operators, a process engineer, the control system engineer, a maintenance technician and a safety representative.

In absence of quantified variables for use in an optimized model (as shown in Equation 1), the team talked through the merits of manual control versus automated control for all 114 steps in the batch process. In the discussion, the team considered time, system reliability, trust in the automation, confidence in operator skill and training, ability to recover from an upset and other determination variables. The team also discussed the benefits and costs of automating each step compared to keeping it manual and whether the step could be partially automated. The "Automation vs. Manual Control" sidebar (left) shows a representative example of how each step in the design of the process was analyzed.

Because no reliable decision-making model is available, it still is not possible to quantifiably design the optimized mix of automation and manual control into a control system. However, with structured discussion between the operators and the design engineer, a workable, effective and subjectively optimized system can result.

In this example, nearly 50% of the steps in the process were designed to remain either manual or were allowed to have 100% override if automated. Only about 20% were designed to be completely automated without human intervention. Even though some steps were automated and the designers were not comfortable allowing 100% override capability, through discussion, it was decided that override could be granted if a second-level approval was obtained. The remaining steps were designed to allow partial automation based on the perceived workload at these particular points in the batch process.

The design team and the operators who now operate the system deemed this exercise to be valuable. The crews are comfortable with the level of automation, and no process upsets have occurred since this study and design were implemented more than 2 years ago.

Conclusion

While no one tool currently available will guarantee that the control system designer will properly engineer the right amount of automation into the system every time, it is expected that discussion among the relevant parties and a structured analysis will help to ensure effective system performance that produces fewer errors. While it stands to reason that without a human in the equation, no human error can occur, the research literature does not adequately support the claim that automating the control of a process will ensure fewer incidents. Researchers should continue to study this issue as technology becomes more available and powerful. For now, it is appropriate to educate control system engineers about operator ability and limitations and to educate operators about the ability and limitations of automation.

Humans continue to provide valuable input to any system and every control system designer should strive to maximize human input that capitalizes on human characteristics such as judgment, flexibility, experience, adaptability and motivation. At the same time, the engineer must maximize overall system performance by relying on automation to take over for human inattentiveness, inconsistency, and lack of endurance and vigilance, as well as to overcome physical and cognitive limitations. The challenge for the design and the human factors engineering communities is to better understand the relationship between automation and human variables so that appropriate quantification and, thus, appropriate design can be achieved. ■

References

Chapanis, A. (1972). *New approaches to safety in industry.* London: InComTec.

Degani, A. & Heymann, M. (2002). Formal verification of human-automation interaction. *Human Factors, 44*(1), 28-43.

Fitts, P.M. (1951). *Human engineering for an effective air navigation and traffic control system.* Washington, DC: National Research Council.

Haight, J.M. & Kecojevic, V. (2005). Automation vs. human intervention: What is the best fit for the optimal system performance? *Process Safety Progress Journal, 24*(1), 45-51.

Jamieson, G.A. & Vicente, K.J. (2005). Designing effective human/automation/plant interfaces: A control-theoretic perspective. *Human Factors, 47*(1), 12-34.

Kaber, D.B., Wright, M.C., Prinzel, L.J. III, et al. (2005). Adaptive automation of human/machine system information processing functions. *Human Factors, 47*(4), 730-741.

Kirlik, A. (1993). Modeling strategic behavior in human/automation interaction: Why an "aid" can (and should) go unused. *Human Factors, 35*(2), 221-242.

Larson, G. (1986). *Far Side gallery 2.* Kansas City, MO: Andrews McMeel Publishing.

Lee, J.D. & See, K.A. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors, 46*(1), 50-80.

Lorenzo, P.E. (1990). *A manager's guide to reducing human errors: Improving performance in the chemical industry.* Washington, DC: Chemical Manufacturers Association.

Louis, M.R. & Sutton, R. (1991). Switching cognitive gears: From habits of mind to active thinking. *Human Relations, 44*(1), 55-76.

Madhavan, P., Wiegmann, D.A. & Lacson, F.C. (2006). Automation failures on tasks easily performed by operators undermine trust in automated aids. *Human Factors, 48*(2), 241-256.

Molloy, R. & Parasuraman, R. (1996). Monitoring an automated system for a single failure: Vigilance and task complexity effects. *Human Factors, 38*(2), 311-322.

Mumaw, R.J., Roth, E.M., Vicente, K.J., et al. (2000). There is more to monitoring a nuclear power plant than meets the eye. *Human Factors, 42*(11), 36-55.

Paradies, M. & Unger, L. (2000). *TapRoot: The system for root cause analysis, problem investigation and proactive improvement.* Knoxville, TN: System Improvements Inc.

Parasuraman, R., Mouloua, M. & Molloy, R. (1996). Effects of adaptive task allocation on monitoring of automated systems. *Human Factors, 38*(4), 665-679.

Parasuraman, R. & Riley, V. (1997). Humans and automation: Use, misuse, disuse and abuse. *Human Factors, 39*(2), 230-253.

Petersen, D. (1996). *Human error reduction and safety management.* New York: Van Nostrand Reinhold.

Peters, G. (1966, Jan.). Human error: Analysis and control. *Journal of the ASSE,* 9-15.

Petroski, H. (1994). *Design paradigms, case histories of error and judgment in engineering.* New York: Cambridge University Press.

Prinzel, L.J., Freeman, F.G., Scerbo, M.W., et al. (2003). Effects of a psychophysiological system for adaptive automation on performance, workload and the event-related potential P300 component. *Human Factors, 45*(4), 601-613.

Reising, D.V.C. & Sanderson, P.M. (2004). Minimal instrumentation may compromise failure diagnosis with an ecological interface. *Human Factors, 46*(2), 316-333.

Salthouse, T.A. (1984). *A theory of cognitive aging.* Amsterdam: Elsevier.

Senders, J.W. & Murray, N.P. (1991). *Human error: Cause, prediction and reduction/analysis and synthesis.* Hillsdale, NJ: Erlbaum Associates.

Sheridan, T.B. & Ferrell, W. (1974). *Man/machine systems: Information, control and decision models of human performance.* Cambridge, MA: MIT Press.

Sklar, A.E. & Sarter, N.B. (1999). Good vibrations: Tactile feedback in support of attention allocation and human/automation coordination in event-driven domains. *Human Factors, 41*(4), 541-552.

Waterson, P.E., Older Gray, M.T. & Clegg, C.W. (2002). A sociotechnical method for designing work systems. *Human Factors, 44*(3), 376-391.