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# Ironies of Automation: Still Unresolved After All These Years

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*Abstract*—**Lisanne Bainbridge's 1983 paper, Ironies of Automation, has had considerable influence on human–machine research, prescience in predicting automation-related concerns that have led to incidents and accidents, and relevance to issues that are manifested to this day. Bainbridge's paper displays influences of several researchers, but Rasmussen's work on operator performance in process systems has perhaps been most influential. Unlike those who had earlier considered operator input a unidimensional aspect of system performance to be considered equally with other system elements, Rasmussen viewed operator performance as multidimensional—to be considered, with training and experience, in examining the operator role in system operations. Expanding on his work and applying it to automated systems, Bainbridge described how automation fundamentally altered the role of the human operator in system performance. Requiring the operator to oversee an automated system that could function more accurately and more reliably than he or she could, can affect system performance in the event that operator intervention is needed. The influence of the insights Bainbridge provided on the effects of automation on system performance could be seen in both research on automation and in the recognition of ironies discussed in subsequent automation-related accidents. Its inspiration to researchers, accident investigators, regulators, and managers continues to this day as automation development and its implementation continue unabated.**

*Index Terms*—**Automation, ergonomics, human factors, man–machine systems, vehicular automation.**

## I. Introduction

IT IS only right that in recognizing the contribution of human–machine researchers, Lisanne Bainbridge, whose work, "Ironies of Automation," [1] remains among the most influential of those on this topic, should be acknowledged. Even absent the paper, her work in cognitive psychology and systems operations would be worthy of recognition; with it her research takes on particular import. The passage of time has only heightened the importance of her work and its influence on our understanding of human interaction with automated systems. The concerns regarding the effects of automated systems on operator performance identified in the paper are as relevant today, when autonomous highway vehicles are being developed for large-scale use, as when the paper was written. Over three and a half decades later, issues with automated systems that Bainbridge had raised still have not been resolved. This is the case despite the considerable research it has inspired, the lessons learned from the widespread implementation of automated systems, and numerous investigations of accidents caused, at least in part, by operator errors through interactions with automated system operations.

The paper's influence can be seen in a variety of ways. At a fairly broad level, the number of works that have referenced the paper is substantial. As of early November 2016, Google Scholar listed 1800 scholarly works that had cited Ironies of Automation. By contrast, other influential works on the subject, such as Weiner and Curry's 1980 *Ergonomics* paper on flight-deck automation [2] listed 564, and Norman's 1990 paper on automation design in the *Philosophical Transactions of the Royal Society of London* [3] was cited 488 times. The number of citations of Bainbridge's work, large as it is, is also increasing at a considerable rate. In the two-week period from late October to early November 2016, ten additional published and presented works cited the paper. Other indices of recognition include a paper revisiting the subject of the initial paper [4], and another, on a related subject, automation law, that adopted its title with only a moderate alteration for the subject addressed [5].

Not only does Bainbridge's paper continue to be cited in scholarly works, its influence on our understanding of the field has been substantial as well. Its impact can be seen in studies of out-the-loop performance [6], automation bias [7], [8], automation complacency [9], mode awareness [10], automation-related errors [11], adaptive automation [12], automation-related skill degradation [13], and the operator role in automated system operations [14], among others.

In this tribute, I explain the background of Ironies of Automation and the nature of its influence on subsequent work. I examine the paper's contemporary relevance by citing automation-related accidents that have occurred since the paper was written, and accidents that illustrate issues Bainbridge raised in 1983, issues that have yet to be resolved. I also identify automation-related concerns that have emerged since the paper was published, describing as she did ironies that, with the hindsight gained from experience, demonstrate the potential challenges to system operations that are inherent in automated operations. Finally, I suggest avenues of research to pursue in light of the issues Bainbridge's paper has raised, avenues also engendered by research conducted since her paper was published, and by advances in the implementation of automated technology.

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## II. Ironies of Automation

Ironies of Automation, a "Brief Paper," totaled less than three pages of text and one of references. But in those few pages Bainbridge described issues of human-automated systems that profoundly influenced subsequent thinking on automation. The ironies she described derived from two fundamental truths, based on the recognition that a system that is free of the possibility of failure is an impossibility because, 1) human operators are integral to sociotechnical systems and removing them from automated system operation does not remove the potential of human error from affecting those operations, and therefore 2) eliminating human error by automating heretofore operator-performed tasks leaves the operator with the responsibility of addressing the consequences of automated system anomalies. In these circumstances, operators would have to address either tasks that the designer had not considered automating or system shortcomings that neither the operator, the system manager, nor the regulator had anticipated. In presenting each human–automation concern as an irony, i.e., a "combination of circumstances, the result of which is the direct opposite of what might be expected," she succinctly identified issues that apply to all automated sociotechnical systems, irrespective of their nature or scope of operations.

When implemented in sociotechnical systems, automation, as a result of its efficiency and reliability, tends to increase its share of what had been operator-performed tasks. The initial irony Bainbridge described addresses the relative influence on operator performance of automation. "The more advanced a control system is," she wrote, "... the more crucial may be the contribution of the human operator" [1, p. 775]. Because of the potential for unrecognized flaws in complex system design, operators must participate in system operations—if for no other reason than to be available in the event that flaws affect operations—to prevent their consequences from being realized and adversely affecting system safety. In fact, the more critical the system, she suggested, the more necessary the human role in maintaining system safety and mitigating the effects of a system malfunction.

Human operators, she argued, are critical components of automated systems and must be recognized as such. Improving safety by removing the human operator will, she wrote, only create additional ironies. Yet, she pointed out that when intervention in an automated system is needed, the skills operators would need to apply are likely to be those skills that automation had been performing in their place, skills that would, as a result, be diminished from the effects of interacting with the very automation that the operator would need to mitigate. In such situations, Bainbridge wrote, "a formerly experienced operator may now be an inexperienced one" [1, p. 775]. Further, in such circumstances operator intervention would be needed at the worst possible time, following a system malfunction. Because the need to intervene would occur only when the automation had failed, or when system anomalies were of such severity that the capabilities of the automation to respond were exceeded, even a fully proficient operator would be challenged to effectively respond in those circumstances.

Moreover, Bainbridge suggested that operators would be additionally disadvantaged in such circumstances by having relatively inadequate knowledge of the automation logic that led to the anomaly in the first place. Such knowledge, which she indicated requires both extensive operator interaction with the automation and system feedback on the effectiveness of such interactions, is difficult to retrieve because automation use leads to a decrease in both system knowledge and system feedback. As she wrote, "the operator who has to do something quickly can only do so on the basis of minimum information, he will not be able to make decisions based on wide knowledge of the plant state until he has had time to check and think about it" [1, p. 776].

Because of research demonstrating that visual monitoring quality deteriorates after about 30 min, extended operator monitoring of automation is limited and is expected to be increasingly ineffective. Effective extended monitoring, she suggested, will likely call for aural alerts to inform the operator when things go wrong, and of course, he or she will then need to continuously monitor the system in the event of an alerting malfunction. Both ironies lead to an additional irony, "the automatic control system has been put in because it can do the job better than the operator, but yet the operator is being asked to monitor that it is working effectively" [1, p. 776].

This insight led to still another irony: 1) because performance parameters can change in dynamic systems, operators need to maintain awareness of the parameters through all phases of system operations, and 2) operators of automated systems will therefore need to monitor systems that were implemented precisely because they can monitor more quickly and reliably than can operators. "If the computer is being used to make the decisions because human judgment and intuitive reasoning are not adequate in this context," she writes [1, p. 776], "then which of the [automation's] decisions is to be accepted? The human monitor has been given an impossible task."

Finally, she noted the potentially adverse effects of automation on operator motivation. A job that is both boring and yet responsible is, according to Bainbridge, "one of the worst types," with deleterious effects on operator attitude and motivation. The result is a job that provides no opportunity, she writes, for operators "to acquire or maintain the qualities required to handle the responsibility" [1, p. 776].

Bainbridge proposed several solutions, predicated on the assumption that automation in sociotechnical systems will perform an increasingly larger share of hitherto operator-performed tasks. She suggested employing enhanced alarms and displays to help operators recognize system failures when monitoring automation, while acknowledging, at the same time, that alarms in themselves may create their own challenges to operator performance. She also proposed (for process industries) automatically shutting down operations when failures are detected, if doing so does not damage the system or make its operations unstable.

To maintain operator manual and cognitive skills during interactions with automation, Bainbridge suggested that operators employ manual system control on occasion, a technique that would enable them to maintain proficiency in diagnosing and responding to system anomalies. As will be discussed, its absence has played a role in an aviation accident. In the event that this was not feasible, she also proposed simulator training sufficient to maintain operator manual control skills. However, as with alarms, she recognized a shortcoming inherent to reliance on simulator-based training; unknown faults cannot be planned to be presented in simulators and, therefore, operators' ability to diagnose and respond to them will be limited.

Finally, Bainbridge called for human–computer research to address the ironies of automation that she had identified. The suggested research was predicated on the belief that, as she wrote, "there will always be a substantial human involvement with automated systems" [1, p. 777].

## III. Perspectives on Operator Performance

Bainbridge's paper was published in 1983, the same year as Rasmussen's seminal paper on skills, rules, and knowledge in human performance [15]. The timing of the papers is not accidental; they followed the 1979 accident at the US nuclear power generating station at Three Mile Island (TMI). That accident, as few others, altered views not only on the safety of civilian nuclear power but on the safety and reliability of the technology applied in general to such complex systems as electrical power generation, mass transportation, and financial systems, among others. The finding of operator errors as causal to an accident in what was widely believed to have been a safe system led to calls from managers, designers, and regulators to eliminate human operators from such systems as a way of eliminating human errors and enhancing system safety. Rasmussen and Bainbridge's works were among those that explained why complying with such calls would only exacerbate possible system difficulties.

Rasmussen [15], recognizing the potential for errors in any system, explained that operator errors were a function of the complexity of the tasks they performed, and their skill and experience in performing them. He suggested considering such errors in terms of the level of complexity of the tasks undertaken and the nature of the operator's response. Given a demanding task, operators' skills and knowledge of operating rules, gained from both training and experience, may not be sufficient to address the tasks. In such circumstances operators would, therefore, need to develop new interactions with the system, based on their knowledge of those systems, to effectively respond. In the event that their knowledge was inadequate, unexpected consequences could result.

Perrow [16] explained the TMI accident and the human errors that led to it as normal outcomes of systems that are of such complexity that operators are unaware of potential interactions within the system. With tight coupling among the subsystems even a relatively minor operator error or component malfunction could "normally" lead to consequences that neither operators nor designers had anticipated, up to and including an accident.

Both Perrow and Rasmussen were among the first to recognize that accidents such as that at TMI were the result not of "bad" operators but of elements of the systems with which the operators were interacting. Both acknowledged that operators were integral to system operations, and that system safety depended upon understanding and addressing error causation rather than attempting error elimination. By examining the systems in which operators worked and focusing on both system design and operator tasks, they implied that potential future operator errors could be reduced.

Rouse and Rouse [17] expanded on previous works on error analysis, particularly that of Rasmussen, and proposed an analysis and classification scheme for operator errors. They described error classification schemes as being behavior-oriented, that is, a function of the operator tasks being performed in the specific domains, task-oriented that focus on the nature of the particular tasks being performed, and system oriented that examine the general systems in which the errors were committed.

Bainbridge's paper, as that of the Rouses, followed in the tradition of Rasmussen and Perrow, albeit focusing on operator-automation interactions rather than on more general operator-system ones. As they, she recognized that operators were integral to sociotechnical systems, but performing according to cognitive psychological principles. Her roots in cognitive psychology are evident in Ironies of Automation. "The change between knowledge-based thinking and 'reflex' reaction," she writes, referring of course to Rasmussen's skill-based and knowledge-based operator performance, "is not solely a function of practice, but also depends on the uncertainty of the environment, so that the same task elements may be done using different types of skill at different times" [1, p. 778]. In that case, she argued, "reliable automatic response is necessary," suggesting the need for operators to gain sufficient experience to enable their automatic or skill-based responses to address specific system states.

Before Rasmussen, Perrow, and others, researchers had generally presupposed that operator performance could be reliably predicted, much as other, mechanical aspects of systems can be. They proposed models to account for the performance of different system elements, including that of operators. For example, Siegel and Wolf [18] developed a model to determine the role of the operator in one human–machine system, aircraft carrier operations, in which a fighter pilot landing an aircraft launches an air-to-air missile. The model assumed that "the operator remembers and executes the correct sequence of subtasks" [18, p. 23]. In 1967 Suggs, examining the operator role in complex systems wrote, "in recent years the idea that man functions as a servomechanism has gained some measure of acceptance" [19, p. 433]. Baron and Kleinman [20], examining manual control of complex systems, viewed the operator "as an adaptive-measurement system . . . [who] decides where he will direct his foveal visual attention on the basis of a preselected optimality criterion" [p. 17]. Preyss and Meiry [21] proposed a stochastic model of operator learning in a manual system control task. As they suggested, the "subject [in their study] is conceptualized in the model as a sequential data-processing system . . . [in which] each element requires a finite time to either process or transmit information . . . " [p. 36]. Scholl [22], using statistical decision theory, developed "an engineering oriented model of the human as a processor of sensory information and an experimental evaluation with visual stimuli" [p. 352]. Rouse later [23] described the human operator as a "suboptimal smoother," who must interpret the data presented to perform the necessary task.

The intent, as he wrote, was to develop a single algorithm to represent the optimal solution of tasks that people perform when "smoothing" or interpreting raw data. A year later, Kleinman and Curry [24] presented models of operator performance while detecting failures in "automatically controlled systems."

Although most of these models dealt with systems in general rather than automated systems, researchers had come to recognize, before Ironies of Automation, that automation was a critical system element and that system performance could be optimized by integrating the human operator with the automation. In 1967, for example, Taylor [25] argued that there was no longer a question as to whether automation would be used in a variety of systems, the question was when such implementation would take place. Researchers, recognizing this, proposed models to account for and predict the performance of individual system elements in automated systems [e.g., 26]. Several recognized that the effects of automated systems on operator performance should be studied. Particularly after the TMI accident, researchers suggested that human-automated systems needed to account for potential operator unreliability [e.g., 27, 28].

While acknowledging that automation introduced a new dimension to human–machine systems, few researchers recognized that such systems substantially altered the role of the human operator by introducing the potential for errors that were both qualitatively and quantitatively different from those committed in nonautomated systems. For example, Wickens and Kessel [29] found that operators, when manually controlling a system, detected system failures better than when they had been monitoring an automated system that detected failures. They demonstrated that the quality of operator performance declined when they monitored automation-performed tasks compared to those that they had manually performed.

Researchers were also influenced by a series of aircraft accidents that occurred in the late 1970s, involving automated systems that are considered fairly primitive by contemporary standards. Wiener and Curry [2], in particular, identified a series of accidents that, they argued, resulted from the consequences of replacing operator-controlled tasks with machine-controlled ones. They too predicted that automation would be increasingly implemented in sociotechnical systems (although they restricted their focus to commercial aviation), but as Bainbridge, they took issue with the assumption that automation can eliminate human error.

In identifying specific aviation accidents and automation-related pilot errors, they presaged the considerable attention that researchers subsequently devoted to the effects of automation on operator performance. Like Bainbridge three years later, they raised numerous issues regarding the effects of automation on operator performance. Unlike Bainbridge, their automation-related concerns were a mix of "macro" and "micro" issues, that is, those that applied to broad concerns of automation use as well as to specific potential consequences of that use. The latter included the possibility of crew errors from incorrectly entering data into onboard systems, responding to false alarms, as well as to the type of broader issues that were similar to those that Bainbridge focused on in 1983. These included automation's effects on operational skill retention, performance decrements with extended visual monitoring, and what they referred to as "psychosocial aspects of automation," similar to Bainbridge's discussion of operator motivation.

With the hindsight of over three decades, the influence of both Wiener and Curry's [2] and Bainbridge's [1] papers on contemporary thinking on automation is evident; but Bainbridge's appears to have had a greater impact, if by no other measure than the number of their respective citations in scientific publications. This may be due to the former's focus on aviation exclusively compared to the latter's focus on sociotechnical systems in general. It may also be due to their respective timing; in 1983, the sociotechnical community may have been more receptive to a discussion of potentially adverse consequences of automation than it had been three years earlier. It may also be that Bainbridge's succinct description of the potential consequences of automation was presented in a way that could be grasped by a wider and more influential audience than could the other. Finally, it may also have been that the ironies she described were so fundamental to the nature of automation that both researchers and practitioners could not help but notice its relevance and its import. More likely, it was a combination of these factors that allowed Bainbridge's paper to engender the influence it did.

## IV. Before Ironies of Automation

Bainbridge's research before Ironies of Automation, which began in the late 1960s [30], suggests a traditionally cognitive psychological approach, applied to industrial process settings. For example, her 1972 doctoral work focused on a cognitive task among process controllers [31]. Before that she had worked of what would be considered a "traditional" human factors study on the effect of display type on operator decision making [32].

Her research in the mid to late 1970s examined such cognitive psychological tasks as mental workload assessment [33], and a work suggestive of Rasmussen, an examination of the effects of increasing task demands on operator performance in a simple control task [34]. A year later she published a related work that applied her interest in cognitive psychology to system operations, examining the efficacy of verbal reports on process operators' cognitive activities [35]. She later wrote a book chapter [36] that suggested a need to replace models based on engineering concepts with ones based on cognitive processes, a proposal whose relationship to Ironies of Automation is clear. Shortly after Ironies of Automation, she further examined operator cognitive tasks in process operations [37].

By this time her influence was becoming manifest. Baum and Drury [38, p. 10], for example, devoted considerable attention to her work, concluding that, "a potentially fruitful method of approaching both of these problems is Bainbridge's loose-hierarchical, goal-directed model of the process controller, (in which research) would not only provide models of human performance but also insight into, and validation of, performance measures." After Ironies of Automation, she examined operator cognitive performance during system failures in nuclear power plants.

The arc of her work, as could be seen from this brief review, demonstrates an interest in applying cognitive psychology to the study of operator performance in process industries. It appears natural, in hindsight, that with this focus and the considerable interest following the TMI accident in eliminating (rather than reducing) operator errors in sociotechnical systems, that she would combine her concerns into the Ironies paper.

## V. System Accidents and Ironies of Automation

The merit of a scientific work is typically determined by the quality of its data analysis and interpretation, its advancement of theory, and its influence on subsequent research. To this list I add a fourth, specifically following Ironies of Automation, i.e., the degree to which issues a work raises continue to be relevant and insightful years later. In these respects, the paper has made a substantial contribution indeed.

The paper was among the first to recognize that the implementation of automation in sociotechnical systems alters the predictability of operator performance and that failing to address issues raised by the implementation of automation only increases the likelihood of operator errors. The issues she identified over three decades ago continue to influence researchers, designers, system managers, and regulators to this day. Her influence on regulators could be seen, for example, in guidelines that the US government's National Highway Traffic Safety Administration issued on autonomous vehicle design [39]. The guidelines note that, "new complexity is introduced as HAVs (highly automated vehicles) take on driving functions, in part because the vehicle must be capable of accurately conveying information to the human driver regarding intentions and vehicle performance" [39, p. 22].

While Bainbridge did not cite specific accidents, as Wiener and Curry had done three years earlier [2], when measured against recent automation related accidents the extent of the prescience of her insights is considerable. For example, the irony, "When manual take-over is needed there is likely to be something wrong with the process, so that unusual actions will be needed to control it, and one can argue that the operator needs to be more rather than less skilled, and less rather than more loaded, than average" [1, p. 775], can be seen in multiple accidents. For example, in an accident involving a passenger cruise vessel, the second mate, incorrectly responding to what he considered an automation-related steering anomaly, put the vessel into a series of rapidly increasing oscillations, ultimately leading to a 24° vessel heeling angle. Two hundred and ninety-eight passengers and crew of the 4,454 persons on board were injured as a result [40].

The accident sequence began when the captain and staff captain executed an operating mode of the vessel's integrated navigation system (INS), an automated system that navigated, established, and maintained a vessel course between multiple points, in accordance with course parameters that crew members selected and entered into the system. The vessel's INS, as with many sophisticated automated systems, offered a multitude of options with which to control the vessel, from maximum speed to maximum fuel economy, while considering numerous operator-selected system and environmental options, including parameters such as sea state.

The captain and staff captain entered into the system a sea state that did not match the one the vessel was traversing, not fully understanding the impact of the parameters on vessel steering. After engaging the system, they noticed that the vessel was "wandering all over the place," or producing greater than anticipated turns in attempting to maintain the selected course. They then increased the vessel steering limit—an effort to silence alarms that indicated that the vessel turn limit had been reached. They did not recognize that this exacerbated the vessel steering issue that led to the alarms in the first place by increasing the range of rudder motion controlling steering.

About 17 min after first engaging the INS, the captain and staff captain turned over the vessel watch, navigation oversight, to the second mate, and then left the bridge. Within minutes the vessel turns substantially exceeded those that the vessel experienced before the captain and staff captain had increased the steering limits. The second mate, not understanding the cause of the turns, that is, the increased turn limit and the incorrect sea state selected in the INS, did what he and other operators of automated systems are advised to do when encountering unfamiliar situations. He disengaged the INS and took manual control of vessel steering, attempting to reduce the vessel turn rates. However, he did not recognize that he exacerbated rather than reduced the vessel turns, and worse; he had initiated an oscillatory cycle of increasing vessel turns. Minutes after handing the watch to the second mate, the captain and staff captain, noting the vessel's increasing turns and heeling angles ran back to the bridge and stabilized the vessel, reducing the turns to a steady heading. Both were unaware of the consequences of their INS settings, while the second mate was unaware of the settings and believed, when taking the watch, that the vessel had been appropriately established on its course. None recognized that the vessel was steering in accordance with INS logic and crew-selected parameters, and that the parameters themselves were the cause of the anomaly.

The second mate, who was out of the loop in establishing the INS parameters, encountered a situation that to him was inexplicable. As Bainbridge predicted, he was also faced with a situation that was "difficult for him to interpret whether the feedback shows that there is something wrong with the system or more simply that he has misjudged his control action" [1, p. 775]. Investigators concluded that, "contributing to the cause of the accident were the captain's and staff captain's inappropriate inputs to the vessel's integrated navigation system, while the vessel was traveling at high speed in relatively shallow water, their failure to stabilize the vessel's heading fluctuations before leaving the bridge, and the inadequate training of crewmembers in the use of integrated navigation systems" [40, p. 54].

Bainbridge described the potential consequences of an operator taking system control from the automation precisely when things go wrong. In that event, she wrote, the operator "will need to make actions to counteract his ineffective control, which will add to his work load" [1, p. 775]. Certainly, in this accident, the mate's disengaging the INS and manually controlling vessel steering were appropriate, but he was unable, given what

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he faced, to diagnose the cause of the steering problems while simultaneously attempting to regain vessel control. As a result, he was unable to do either effectively. The consequences of his actions followed almost precisely Bainbridge's predictions regarding an operator in these circumstances. "If he takes over," she wrote, "he may set the process into oscillation. He may have to wait for feedback, rather than controlling by open loop, and it will be difficult for him to interpret whether the feedback shows that there is something wrong with the system or more simply that he has misjudged his control action" [1, p. 775].

This was, of course, not the first time investigators had encountered an accident after an automated system anomaly. For example, in an accident that preceded the vessel accident by over two decades, a Boeing 747-SP enroute to San Francisco from Taipei, Taiwan, lost power in one of its four engines while the aircraft was cruising at 41 000 feet mean sea level, about 300 mi from its destination [41].

As a result of the asymmetry that resulted from the difference between the thrust that the two functioning engines produced on one wing compared to that of the one functioning engine on the other, the airplane's nose was pushed in the direction of the failed engine. The autopilot, which was controlling the aircraft's flight path, continued to steer the aircraft, but with continuously increasing inputs to maintain course. When it reached the limit of its ability to maintain the course it sounded an aural alert and disengaged itself from airplane control, at which point the airplane entered a steep, spiraling dive. With no immediate recognition and comprehension of the situation they faced, the pilots were unable to regain aircraft control. The airplane was within seconds of striking the water when the gravitational forces exerted on the structure pulled the landing gear from its retracted position and extended them. This slowed the airplane's speed, thereby allowing the pilots to recognize and effectively respond to the situation they were facing, regain airplane control and proceed to the closest airport, the intended destination of San Francisco. They were able to safely land the damaged airplane but investigators nonetheless faulted the captain, for, among other things, "his failure to monitor properly the airplane's flight instruments which resulted in his losing control of the airplane" [41, p. 34]. They suggested that had the captain disengaged the autopilot and quickly taken manual control of the airplane upon the loss of engine thrust, something that all pilots are trained to do, the accident would likely have been avoided.

In their report, investigators did not mention Bainbridge's work, which had been published several months before they completed their work. They did not mention her description of automation anomalies limiting the ability of operators to diagnose and correctly respond to them, nor did they address the challenges operators face in monitoring automated systems for hours on end, as these pilots had attempted. "It is impossible for even a highly motivated human being," she wrote, "to maintain effective visual attention towards a source of information on which very little happens, for more than about half an hour. This means that it is humanly impossible to carry out the basic function of monitoring for unlikely abnormalities . . . " [1, p. 776].

Crews in both the passenger vessel and the Boeing 747 SP accidents displayed errors that, in an over 20-year interval, matched what Bainbridge had predicted in 1983. In both accidents operators were unable to understand and identify the cause of the automation-related anomalies they encountered. One, the Boeing 747-SP accident, also demonstrated the challenges that automation presents to operators monitoring systems for extended intervals, with monitoring performance increasingly deteriorating the longer the time operators spent monitoring.

Because of the difficulties operators face in extended visual monitoring, Bainbridge suggested that they would need to be assisted "by an automatic alarm system connected to sound signals." However, adding alarms, while useful to enhance operator recognition of system faults, can create other difficulties, not the least of which is the real possibility of loss of operator sensitivity to alarms that frequently alert. Operators repeatedly exposed to alerts from false alarms have, on occasion, acted to silence them, an understandable but potentially critical act that can mean the difference between a catastrophic accident and a system anomaly. Investigators determined that such operator action led to a fatal 1987 passenger train accident in which 16 passengers and crew were killed [42], [43]. Other possible consequences of extensive and/or repeated aural alerts include the presentation of a multiplicity of alarms during a high workload period, a situation that will exacerbate rather than enhance an operator's ability to recognize the underlying cause of the alarms. As when operators must take system control from automation in response to an anomaly, the challenges of system diagnosis and control while multiple alerts are sounding are considerable. In 2009 the pilots of an Airbus A330 encountered this situation while at cruise altitude over the Atlantic, on a nighttime flight from Rio de Janeiro to Paris [44]. The multiple, simultaneous, speed and stall-related alarms interfered with their ability to diagnose the cause, frozen and blocked pitot tubes. The pilots were unable to regain airplane control and it crashed into the ocean, killing all onboard.

Finally, an accident in which human life was not directly threatened further reveals the difficulties operators face in Bainbridge's suggestion of using alarms to address operator performance during extended visual monitoring of automated systems. Determining the causes of alarms when more than one potential anomaly could initiate them can be challenging in normal operations, but it is especially so in unexpected situations, when operator expectancies can influence diagnosis—and the potential consequences of misdiagnosis can be considerable. In 2010, a rupture in a petroleum pipeline led to the spilling of over 800 000 gallons of oil into a river near Marshall, Michigan [45]. The cleanup cost the company over $1 billion, one of worst pollution incidents in United States history.

Almost immediately after the pipelined ruptured, alarms in the pipeline control center, located hundreds of miles away in Edmonton, Alberta, Canada, alerted pipeline operators to the event, but for over 17 h they misdiagnosed the cause of the alarms, until a company employee personally informed them, from the site of the rupture, of the nature of the accident. They had continued to believe that the alarms had been caused by a "column separation," a break in pipeline product flow caused by

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unequal gravitational forces exerted on a pipeline as it rose and fell with changes in the terrain.

The pipeline control center operators mistakenly applied procedures to the rupture that were intended for a response to a column separation. They increased pipeline pressure to eliminate the column separation, the wrong response to a pipeline rupture as it causes the product to flow freely through the rupture and into the environment. On two occasions, for just less than an hour and a half in total, operators engaged the pumps in an effort to increase product pressure within the pipeline to reduce the perceived column separation, thereby exacerbating the consequences of the environmental damage from the initial rupture.

This inability to correctly diagnose multiple alarms also displayed an additional automation-related irony that Bainbridge had described. Operators called in supervisors to assist them in diagnosing the problem. But as she pointed out, "the supervisor too will not be able to take-over if he has not been reviewing his relevant knowledge, or practising a crucial manual skill" [1, p. 776]. In this instance, the supervisors, as the operators, were unable to identify the cause of the rupture. The supervisors' diagnostic errors led, according to investigators, to a breakdown in team performance by their agreeing with the operators' misdiagnosis of the cause of the alarms and hence, the response. Investigators noted that as a result a subordinate became "the de facto team leader because his conclusions provided an explanation for the Line 6B situation that affected the team's perceptions and actions regarding (the problem with) the line" [45, p. 94].

## VI. New Ironies

Bainbridge's 1983 paper described ironies that, unresolved, led, and continue to, lead to accidents. As automation has been implemented in an increasing variety of systems and applications, new ironies of human–automation interaction are being recognized. For one, automation, which can enhance system performance through its reliability and accuracy, can also disguise operator performance shortcomings. Whereas Bainbridge predicted that automation use can lead to manual and cognitive performance degradation, one accident indicates that preexisting degraded performance can be obscured through automation use. This was seen in a 1994 accident in which a turbo-prop passenger airplane crashed on approach to Columbus, Ohio, USA [46]. The aircraft, a Jetstream 41, was equipped with a sophisticated autopilot that could execute a precise vertical and lateral flight path, in accordance with pilot-entered flight parameters. However, unlike other highly automated aircraft, airspeed control was not automated but instead was manually controlled.

The captain had demonstrated performance shortcomings before the accident. After operating single-engine general aviation and multi-engine charter flights, he was hired by the airline and trained as a first officer. However, he failed his first flight examination to qualify as a first officer, the result, according to investigators, "of difficulties with instrument approaches . . . " among other deficiencies. He received additional training and qualified on his second attempt. After flying as a first officer for about a year and a half, he attempted to upgrade to the captain's position on a more complex aircraft than those he had previously operated, the type that was involved in the accident. That aircraft was equipped with an automated flight control system, his first experience with aircraft automation. After completing training, he failed the flight examination necessary to qualify as a captain on that airplane. According to the flight examiner, the pilot did not properly execute an instrument landing system approach, one that is flown to the runway according to precise vertical and lateral guidance. His attempted approach in the examination resulted in a pilot-induced oscillation and a stall warning. Again, he received additional training and subsequently qualified on his second attempt. Failing flight examinations, which air transport pilots are required to undertake at least annually, when qualifying to fly at different positions on an airplane, or when qualifying on a different model aircraft, is highly unusual. According to the director of flight training at a different airline, about 2% of pilots at the airline with which he was associated failed these examinations [47].

A first officer who had flown with the captain in the month before the accident told investigators that the captain typically engaged the autopilot when flying instrument approaches, thereby delegating flight path control to the automation. So long as his airspeed control was acceptable, he could reasonably expect the automation to execute the approaches properly. However, meteorological records indicate that, for at least the 90-day period before the accident in the flights the captain had conducted, visual conditions, where external visual references facilitate airplane and manual airspeed control, had prevailed. By contrast, the accident flight was conducted in instrument meteorological conditions, accompanied by freezing temperatures and light snow. In these circumstances, no external visual cues are available to support pilots in flight path control; they must rely exclusively on aircraft instruments to ensure that the autopilot's control of the airplane flight path is accurately executed.

On the accident flight the automation maintained effective and accurate aircraft control; however, his focus on the flight path was such the captain failed to monitor the airspeed, allowing it to deteriorate to below the stall speed. Although he was able to monitor airspeed when external visual cues were available, in the instrument conditions that prevailed at the time he was unable to do so effectively. He failed to respond when this key element of the approach, one that was outside of the autopilot's control, had deteriorated to the point that a response was necessary.

Accidents also illustrate an additional irony of automation; even relatively minor anomalies in complex sociotechnical systems can increase the severity of potential consequences through operator interaction with automation. This can be seen in two catastrophic accidents in which air transport pilots flew into terrain, killing nearly all onboard their aircraft. In both accidents the aircraft were equipped with displays associated with automated flight management systems, providing the pilots with readily interpretable information, obviating the need for cognitive effort to determine near term flight paths. Pilots of earlier aircraft had to determine their flight paths based on examining their charts, calculating airspeed, present position, wind direction and velocity, and then manually determining from the data the flight path in relation to the current airplane position.

In 1992, an Airbus A310 flew into terrain near Kathmandu, Nepal [48]. While the two pilots were preparing the aircraft for the approach into Kathmandu, they encountered difficulty extending the flaps. Because this approach was to be conducted through the mountainous Himalayan terrain, pilots were required to configure their aircraft correctly before initiating the approach; they were prohibited from initiating an approach and attempting to configure their aircraft subsequently. As required, after encountering the difficulty the accident pilots discontinued the approach to Kathmandu, configured the airplane properly, and continued flying to the point where they could reinitiate the approach. However, while preparing to reinitiate the approach from its starting point, the Nepalese air traffic controllers and the Thai pilots, both communicating in English, had difficulty in the former's providing and the latter's comprehending the flight clearance to the waypoint at which the approach was to be initiated. Then, while the crew used the automation to identify and locate the waypoints needed to execute the approach, the airplane continued on its flight path without their recognizing that they had continued flying beyond the waypoint, away from the desired approach point, and towards mountainous terrain. The airplane struck terrain just as the first officer conveyed concern about their flight path to the captain.

Two years later a Boeing 757 struck mountainous terrain near Cali, Colombia [49], in circumstances that parallel many of those in the Kathmandu accident. Here too the crew used the airplane's automated flight management system to control the flight. However, the captain misinterpreted an air traffic controller's clearance from "cleared to Cali" to "cleared direct to Cali" and as a result reprogrammed the flight management system to fly to the beacon that served as the starting point for the approach they were to execute. In doing so, he did not recognize that the flight management system deleted the waypoints between the airplane's position and the approach initiation point. Although the system performed as designed, the pilots were unable to determine why they were unable to retrieve the necessary waypoints. When controllers told them to report passing over one of the deleted waypoints, neither pilot was able to locate it through the automation. After repeated, unsuccessful attempts to locate the beacon through the automation, they manually turned the airplane back to Cali, but the airplane struck a mountain thereafter.

These accidents reveal how even relatively minor errors, reconfiguring an airplane incorrectly and misinterpreting a controller's clearance, can become accidents in the event that operators are unaware of the cause of automation-related anomalies. In both of these accidents it is possible, if not likely that the errors of failing to predict near term flight path and failing to recognize the airplane's proximity to waypoints would have been diagnosed and mitigated in less-automated systems. Instead, the consequences were exacerbated by the crew's use of the automation to mitigate the difficulties they faced. An additional irony, of course, is that the pilots on both aircraft used the automated systems to resolve issues that were caused, in part, by their interactions with those automated systems in the first place. Using those same systems to resolve the difficulties was ineffective and in both instances the consequences were catastrophic.

It has also been recognized that operator use of increasingly sophisticated automation has also led to an outcome that Bainbridge recognized at the time of her paper, subsequent degradation of operator skills fundamental to system operations. Commercial pilots typically learn to fly on relatively unsophisticated, nonautomated aircraft and then progress through more complex ones with increasing performance capabilities. Regardless of how they learn to fly or the sophistication of the aircraft they operate, the elements of piloting learned from their earliest exposure to flight operations remain the same. These include the need to maintain continuous awareness of airspeed, altitude, and location. As the accident in Columbus, Ohio, USA, demonstrated, loss of awareness of one can lead to an accident.

However, accidents have occurred in which well-trained pilots, with good performance histories, flying sophisticated highly automated aircraft, lost airspeed awareness as a direct result of their delegating airspeed control to the automation (or the autothrottle system). On approach and landing, precise airspeed control is mandatory; even small variations from the target reference airspeed (a function of airplane weight and landing configuration) can be catastrophic. Airspeeds a few knots over reference speed can lead to an aircraft running off the runway and airspeeds a few knots below can lead to a stall and/or runway impact.

Yet, at least three commercial accidents occurred over an approximate 30-year period in which the pilots committed identical errors, failing to monitor their airspeed after delegating airspeed control to the automated speed control system. Because commercial aircraft accidents are typically investigated by governments, working under international rules and standard investigative protocols, and because their subsequent accident investigation reports are widely read by pilots, airline management, and regulators, accidents in which pilots commit identical errors are rare. The industry typically responds to the errors by modifying pilot training, procedures, and/or oversight, depending on the nature of the error and the type of response needed.

In February 1984, a McDonnell-Douglas DC-10-30 ran off the runway at New York's John F. Kennedy International Airport and was destroyed, resulting in minor injuries to 11 passengers and crew [50]. The aircraft touched down at a considerably higher airspeed than the 155 kn that the pilots had selected and entered into the autothrottle system, the airspeed appropriate for the approach and touchdown speed at the airplane's weight and landing configuration. Rather, the aircraft was actually flown 30 kn higher than that and the pilots were unable to stop the airplane on the available runway upon landing. Investigators determined that a malfunction in the aircraft's autothrottle had led to the excessive airspeed. They attributed the accident, in part, to the pilots' "overreliance on the autothrottle speed control system which had a history of recent malfunctions" [50, p. 47].

Despite the results of the investigation of this accident and the identification of the particular crew error, 25 years later, in February 2009, a Boeing 737-800, with a more sophisticated autothrottle and autopilot system than that found on the DC-10-30, crashed while on approach to Amsterdam [51]. The airplane was destroyed and the three pilots (one was serving as a safety pilot), a flight attendant, and five of the 117 passengers aboard, were killed in the accident. The pilots had entered into the flight management system an approach airspeed of 144 kn, but the autothrottle malfunctioned in this accident as well. Here too the pilots failed to monitor the airspeed on approach, allowing it to deteriorate to 107 kn, too low to maintain flight. Investigators concluded that the accident occurred, in part, because of the crew's "failure of monitoring the airspeed" [51, p. 7]. In both accidents the pilots manifested errors that Bainbridge had described in 1983, the failure to recognize an automation-related anomaly and the failure to operate the system effectively following recognition of the anomaly.

While it can be argued that even two accidents with nearly identical pilot errors in a 25-year period are unusual, four years later yet another accident, with the same pilot error, occurred. In July 2013, a Boeing 777-200ER crashed while on approach to San Francisco International Airport, destroying it and injuring 52 of those onboard, three of them fatally [52]. The airplane struck the edge of the runway at an airspeed of about 20 kn lower than the pilot-selected one of 132 kn. Only seconds before the accident, also when it was too late, the pilots recognized the low airspeed and attempted to correct it. Investigators determined that the autothrottle had entered an operating mode that no longer controlled airspeed, in the absence of pilot action to do so. The pilots had, as a result, to manually control it; but they were unaware that the autothrottle had disengaged from airspeed control.

Although no automation-anomaly occurred in this accident, the error the pilots committed was the same as that the pilots had committed in the other two; they did not recognize that the airspeed had decreased to an unsafe one until they were unable to prevent the accident. Their error was based not on a system anomaly but on their unawareness that the airspeed operating mode had changed and that the automation was no longer controlling airspeed. The system provided only a relatively small visual cue regarding the particular autothrottle mode that was engaged, a cue that was difficult to recognize in a period of high workload. With no associated aural cues to alert the pilots, and their attention focused on the flight path, they were unaware that the airspeed control mode had changed and that they needed to manually control the airspeed. Investigators determined that the airplane had disengaged the automated speed control in response to a pilot action of manually reducing thrust.

Further, investigators learned that Boeing had not informed its customers that, under certain circumstances, autothrottle control of airspeed could end. Neither these pilots, company flight managers, nor its flight instructors, were aware of this system feature. Nonetheless, as with the previous two airplane accidents described, the pilots' failure to effectively monitor airspeed while on approach led to the accident. Investigators determined that the accident was caused, in part, by "the flight crew's inadequate monitoring of airspeed" [52, p. 129].

Repeated identical operator errors in a system as thoroughly overseen as commercial aviation, where accident reports and information about accidents are disseminated to airlines and regulators worldwide, and where manufacturers regularly inform their customers of investigative findings, reveal system breakdowns at multiple levels. The identical, repeated, error of failing to monitor airspeed that is believed to be under automation control, in the mistaken belief that the automation was effectively maintaining it, illustrates yet another irony of automation. Repeated exposure to human–automation interaction errors does not necessarily resolve the cause of the errors. This irony has, if anything, increased in scope with additional exposure to and experience in automation operations.

Designers, have in effect, provided more functionalities than operators need to effectively control their systems, or that they can reasonably be expected to master during their training [53]. In commercial aviation automation functionalities allow pilots to select airspeed, climb/descent rate, and route, as well as offer options on how to fly the selected courses, such as economically, quickly, quickly during a climb, and so on. But these also require operators to fully understand the scope of the automated functionalities, their capabilities, and their effects on system performance. For example, in the vessel heeling accident cited previously, the crew could not only select a routing and speed for optimal speed or economy; they could match the sea state to the selected route to optimize passenger comfort. By being unaware of the consequences of entering the "wrong" parameter within the multiplicity of INS functionalities available, the vessel captains exacerbated the steering anomaly that they had created through the automation. The number of vessel INS functionalities was more than the captains could reasonably use for optimum course control, and too numerous to allow them to acquire, within the training program provided, the expertise necessary to understand the consequences of selecting an inappropriate navigation control mode.

Yet designers have continued to add automation functionalities to the systems they design. On the Boeing 777, as noted, the system changed the speed control mode in response to pilot manual thrust control, a routine pilot action but on this highly automated aircraft a control mode response of which neither they nor the airline was aware. Increasing the number and sophistication of functionalities requires operators to undergo additional training to obtain the expertise needed to understand and properly use them. Often the training necessary to do so is beyond what companies can reasonably provide. As a result, although operators who complete system training are considered to be fully qualified in the systems they control, often, as seen in the vessel heeling accident, they are unable to understand the application of at least some of the functionalities.

The Federal Aviation Administration reviewed the implementation of advanced automation in United States commercial aircraft in 1996 [54] and again in 2013 [55], although the latter was not conducted in conjunction with the 2013 Boeing 777 accident. In the almost two decades between the studies, the US commercial aviation industry experienced an almost fleet wide replacement of aircraft from those with relatively primitive automation to those with sophisticated, advanced automation. Yet, in its 2013 report the Federal Aviation Administration noted that pilots tend to learn to use the automation not during their training periods but during actual system operations. As the agency observed, “in many cases the pilots train themselves during unsupervised line operations” [55, p. 34].

The reasons for the training shortcomings are influenced largely by financial considerations. Training is a cost and not a revenue generator, and because training is often regulated in socio-technical systems, training beyond regulator requirements and beyond that needed for subsequent skill assessments makes little economic sense. But the consequences of adding automation functionalities beyond what operators need to effectively control their systems, with training that does not address the totality of system functionalities, results in operators learning to master automation functionalities ad hoc, in operational environments that are not conducive to gaining expertise, from individuals who may not possess the necessary expertise themselves, and with no established or required standard of proficiency to guide them. In such circumstances operators could obtain erroneous information about automation capabilities and performance, and form operator teams with those of unequal automation-related expertise. In the vessel heeling accident, for example [40], the recording of the bridge conversation between the two captains showed that the staff captain believed he had considerably more automation-related expertise than he displayed in this accident, and the captain, not knowing the staff captain’s lack of expertise, sought to learn about using the INS automation functionalities from him, an operator who did not possess the requisite expertise. This situation reveals an additional irony; operators can become qualified to operate automated systems without possessing the expertise necessary to be fully conversant with the capabilities of the systems they operate.

Bainbridge called for relevant automation training by suggesting that operators be given opportunities to practice manual control during actual system operations, and if not possible, by providing similar experiences in system simulators. But the B-777 accident illustrates that this suggestion, though worthwhile, may not be implemented so long as companies and regulators do not recognize its benefits. The accident airline, for example, required its pilots to operate the airplane through full automation as much as possible and discouraged even occasional manual operation.

Because there is no industry-wide or regulator requirement mandating the extent to which aircraft, or other automated systems, should be operated manually or automatically, there is no recognized standard within industries to guide operators on the optimum extent of automated/manual system control. Operators in systems with no requirement for manual control can have no manual operating experience and therefore will be unprepared to respond to systems with unexpected automation consequences. So long as the systems function as intended and expected, this will not be a problem. But, as Bainbridge pointed out [1, p. 776],

> . . . the automatic control system has been put in because it can do the job better than the operator, but yet the operator is being asked to monitor that it is working effectively. When manual take-over is needed there is likely to be something wrong with the process, so that unusual actions will be needed to control it, and one can argue that the operator needs to be more rather than less skilled, and less rather than more loaded, than average.

Further, although Bainbridge advocated using simulators for training, the Airbus A330 accident [44] demonstrated that simulators, as any device, are limited in their ability to enhance operator problem solving in response to anomalies. Presenting them with unexpected or anomalous situations in simulators will prepare them to recognize and respond to those situations, but that ability may not necessarily translate to recognizing and responding to situations that are similar, but not identical, to those presented. Investigators acknowledged this in their investigation of the pipeline accident described previously. Training that the pipeline controllers received on system simulators had become routinized over time, and when encountering the accident scenario, they were unprepared to recognize and correctly respond to it [45]. Researchers have also observed this phenomenon in a study of pilots of automated aircraft [56].

## VII. Ironies and the Future

In the three and one half decades since Ironies of Automation was published many changes have occurred with regard to the implementation of automation, as well as with our understanding of the human–automation interaction. Yet, the ironies Bainbridge described in 1983 still affect operator performance today, and errors and accidents involving operator-automation interactions continue to occur. The ironies remain unresolved, but it is reasonable to ask: can they ever be resolved? Bainbridge’s ironies, and much subsequent research on automation, presupposed that because no system is perfect or can address every possible anomaly, human operators are required to be available in case they are needed to mitigate the consequences of, or to prevent, system anomalies from adversely affecting system safety. However, human operators also bring their own potential anomalies to systems, as well as the potential for anomalies through the interaction of the two. Until developers can provide credible assurance that the systems they develop will be free of potential anomalies, an impossibility at present and for at least the near term, if not for the indefinite future, it is reasonable to assume that regulators, companies, operators, consumers, and the general public, will demand that human operators be involved in automated system operations. Therefore, it is also reasonable to assume that, as a result, the ironies of automation will not be resolved. The importance of the paper has consequently not diminished over time; it can well be argued that, if anything, it has increased. This is particularly true as automation implementation has increased well beyond what Bainbridge had considered in 1983.

This is not to say that they are not currently being addressed. The contribution of Bainbridge’s article was not only to point out the fundamental flaws of previous suggested approaches for system design and operation, but to propose means of addressing those that were identified. Perhaps a more reasonable question to ask from her work is: how well have the ironies of automation been addressed and how safely are systems that have implemented automation been operating?

Today the frequency of sociotechnical system accidents is lower than it was as recently as 20 years ago, a trend that may likely continue. The frequency of accidents involving air transport aircraft, chemical refineries, and nuclear power generating stations, among other industries, has decreased. The most recent fatal commercial jet transport accident in the United States was in 2013, the B-777 accident described earlier in this paper [52]. Before that the most recent fatal commercial aviation accident in 2009, in which the aircraft involved was a turboprop aircraft. By contrast, when Ironies of Automation was published in 1983, a frequency of two to three major air transport accidents per year in the United States was not uncommon.

While the lower sociotechnical system accident frequency may be the result of a short-term statistical aberration, it is more likely that system operations have indeed become safer, partially the result, among other factors, of more reliable hardware and software, better operating procedures, improved safety oversight, and enhanced operator training. For example, systems in aviation have been developed and implemented to inform pilots of predicted proximity to terrain and to adverse weather. These systems warn pilots when their flight paths are predicted to approach terrain in sufficient time to enable them to recognize and avoid the terrain. When combined with onboard weather radar and automated flight management systems, displays also inform pilots of their predicted proximity to storm cells. This information, as terrain information, presented in a readily interpretable manner, has gone far to decrease the number of controlled flight into terrain accidents and to reduce the frequency of aircraft encounters with adverse weather. Similarly, systems have also been implemented that warn pilots of aircraft on conflicting flight paths, providing them with guidance to avoid the impending collisions.

Accident investigations have also served to identify heretofore unrecognized system shortcomings, such as the B-777 autothrottle control mode that changed without effectively informing the pilots, enabling designers, operators, managers, and regulators to identify and address system deficiencies that had gone unrecognized. As an increasing number of deficiencies become identified and addressed through investigations, the number of accidents resulting from such system-influenced operator errors, maintenance anomalies, or procedural deficiencies, among others, is expected to decrease.

Tools have also been developed and implemented that, with technological improvements, have increased the ability of managers to identify and act on system shortcomings. For example, aircraft flight data recorders and vessel data recorders, both developed primarily for accident investigations, now provide data for operational purposes as well. Companies analyze the data recorded on these devices to detect and address operational anomalies. They can thus discover, for example, whether the aircraft they operate are descending into particular airports at excessive rates, or whether vessel crew are executing poor approaches into selected ports. The analyses of data from these recordings allow airlines and shipping companies to modify training and/or procedures as needed to mitigate opportunities for hazardous operations. Companies have also implemented safety management systems, with which they collect and examine operational data that could identify system anomalies, also providing them with information to identify and mitigate operational risks.

Finally, and to a large extent because of Ironies of Automation and automation-related accidents, research has expanded our understanding of the potential consequences of automation on operator and system performance. We have now identified, for example, certain designs and circumstances that enable operators to lose track of system operating modes, or to defer to automation in spite of misgivings they may have had to do so. We understand to a greater degree than before the effects of automation on operator workload, and how automation can lead to deteriorating operator vigilance and decreased system situation awareness. Improved training and better operating procedures can be implemented, as a result, to enable operators to respond to automation-related issues that would otherwise have previously compromised system safety.

Nonetheless, as the implementation of automation increases, the issues that Ironies of Automation raised now apply to settings well beyond those envisioned three and a half decades ago. Today automation implementation has become so widespread that Hancock [57, p. 453] suggests that we cannot "amend, direct, stop, reverse or even substantively influence this proliferation of automation." As a result, it can be argued that it has become especially necessary to revisit Ironies of Automation. For example, millions of people worldwide use smartphone technology in ways that were unprecedented as recently as few years ago. The technology provides users ready access to information and information analytics in intuitive and user-friendly ways well beyond the information the highly trained operators whom Bainbridge studied could access. Yet, by making smart phone technology as accessible, appealing, and affordable as they have, developers have also made it distracting to those who use them when attempting to perform other tasks. Accessing smart phones during tasks as simple as crossing the street increases the potential for error and for a subsequent accident. As a result of this phenomenon, a new type of accident has been recognized, one due to a distracted user. In one of the first accidents to illustrate this, a distracted passenger train operator in 2008 failed to attend to a stop signal while texting bystanders, causing his train to collide with a freight train. Twenty five people, including the train operator, were killed and 101 injured in the accident [58].

Since then smartphone were use has become even more widespread, and the number of applications they offer has increased considerably. "Distracted operator accidents" have also spread beyond sociotechnical systems to automobile operations and pedestrians. A recent US Department of Transportation study found, in a sample of automobile accidents occurring between 2005 and 2007, that 94% of the accidents were due to driver-caused errors, such as decision errors of driving too fast for conditions, misjudging distances, etc. [59]. Because the study did not go beyond that to determine factors that led to the errors, factors that are often beyond the ability of local authorities to investigate, the extent to which fatigue, smartphone distraction, inexperience, and impairment from drugs, alcohol, or medical conditions, for example, were antecedents to those errors was not addressed.

Yet, there is no question that these antecedents lead to highway accidents as they have in other systems, if not more so in a system that lacks the oversight, extensive regulation,

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operator training requirements, and system safety features found in more complex sociotechnical systems. A subtext of automobile manufacturers and technology companies such as Google, in their designing and promoting highly automated vehicles, is that these vehicles can compensate for the types of operator-related error antecedents commonly seen in highway accidents. Yet, the implementation of automation in nonsociotechnical system settings raises anew issues regarding human interaction with automation.

Woods [60], noting the many benefits being touted for what he refers to as autonomous technologies, suggests the need to address ironies that Bainbridge had described [60, p.131],

> Today's common beliefs . . . replay what has been observed in previous cycles of technological change. As past work has shown, claims about the effects of future technology change are underspecified, ungrounded, and overconfident, whereas new risks are missed, ignored, or downplayed.

Sebok and Wickens [61, p. 191] describe numerous types of automation failures, including software bugs and hardware failures in which "automation performs as the designer intended but not as the user intended." In developing a model of automation use and tools to predict operator performance with automation, they identified two phenomena that in effect, revisit automation ironies. Black swans, previously used to identify financial system failures, refer here to rare and unexpected automation failures, and lumberjacks, who must address the effects of failures of high levels of automation on the operators. They argue that as lumberjacks must deal with the unintended consequences of felled large trees, operators must do so with systems after automation failures. The higher the level of automation, they note, the greater the potential adverse effects on operator performance, just as the taller the tree, the greater the potential negative consequences of its being felled.

Recent research on the effects on operator performance of automation in other than sociotechnical systems show, not surprisingly, results similar to findings of research conducted decades earlier on performance in sociotechnical systems. For example, Larsson *et al*. [62] found that, when driving simulated, highly-automated motor vehicles, operators both experienced and inexperienced with the technology demonstrated considerably longer reaction times when braking to avoid an unexpected vehicle cutting in front of them than did those operating vehicles manually, i.e., with little automation. Merat *et al*. [63], measuring eye tracking and gaze fixations, and hence attention to the road, of drivers of highly automated and nonautomated simulated vehicles, found that, when encountering situations that called for disengaging the automation, the attention of drivers of automated vehicles continued to vary from the road when compared to that of drivers operating in manual control.

Strand *et al*. [64] compared simulated vehicle driver responses to unexpected and sudden braking of vehicles in front of them. The simulated vehicles differed in the level of automation employed and in degree of percentage of braking effectiveness lost. The greater the degree of vehicle automation, the longer the driver response time to brake. The authors concluded [65, p. 226], "if further automation is added (to vehicles) . . . degraded driver performance is likely to follow."

Similarly, Merat *et al*. [63, p. 275] described what can be considered a contemporary automation irony,

> One argument for increased levels of automation in vehicles has been that of enhanced safety, with driver error and inattention cited as a major contributory factor to crashes . . . however, engagement in other tasks is directly linked to the removal of drivers' attention from the road, and . . . (this) may lead to reduced driving performance.

Given the increasing implementation of automation, Hancock [57] argues that researchers need to address an additional irony of automation, "If you build systems where people are rarely qualified to respond" he notes, [57, p. 453] "they will rarely respond when required,"

Endsley [65] employs a different perspective on increasing automation, what she terms "autonomy," in recognition of its growing implementation and increasing capabilities. She proposed a model of autonomy for designers to consider to respond to what she refers to as "the automation conundrum," or irony, if you will. "The more automation (that) is added to a system, and the more reliable and robust that automation is," she writes [65, p. 8], "the less likely that human operators overseeing the automation will be aware of critical information and (be) able to take over manual control when needed." But she suggests that by attending to the effects of display quality and level of automation on operator workload, situation awareness, and type of operator control desired, designers can enhance the quality of operator response to the automation. Similarly, Stowers *et al*. [66] propose metrics for designers to use to assess the efficacy of automated systems, particularly as applied to vehicles in space exploration. They argue that three general inputs need to be evaluated in such systems, those of the human operator, the machine, and the context in which the system operates. Operator factors include cognitive competencies and interpersonal traits, while machine factors include automation adaptiveness and operating transparency.

A valid argument can be made that the development and large-scale use of autonomous or highly automated vehicles, to illustrate one example, will enhance safety by reducing, if not eliminating errors caused by driver inattention, distraction, fatigue, impairment, and inexperience. But, as with other systems, motor vehicle automation will likely introduce new ironies. To illustrate only a few of the potential issues that this type of automation raises, research is needed to determine that, given driver inexperience is an antecedent to error that leads to accidents, the extent to which automated vehicle operation can increase operator experience sufficient to enable them to effectively recognize and respond to critical situations. Research is also needed to determine how autonomous vehicles can motivate drivers to attend to automated system performance given that the automation has and likely will be marketed as enhancing safety by compensating for operator error antecedents. Further, research is needed to determine criteria for regulators to use to measure operator skills needed to interact effectively with autonomous vehicle automation. For example, should operators demonstrate skills to operate the systems in both manual and automated operating modes or only one, and if both, how should training and licensing requirements change in response?

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The increasing implementation of automation across hitherto manually operated systems and devices will, as Hancock [57] noted, unquestionably continue. Yet, the need for research to enhance operator performance has increased as well, even if the Ironies of Automation may not be resolved. Using Endsley's model for example [65], research is needed to identify the optimal presentation of system data to maximize operator situation awareness of automated system performance. We have also not yet identified, and we need to study and identify, procedures that will enable operators to maximize the safety, reliability, accuracy, and economic operating features of automation, while at the same time optimizing their vigilance and retaining their manual and cognitive operating skills. Research is also needed to identify the optimal information display that will enable operators to readily diagnose the cause of multiple alarms. Finally, we lack the ability to inform regulators and managers of technological changes in sufficient time to enable them to develop the necessary rules to ensure safety before technological advances are implemented. The guidelines that the National Highway Traffic Safety Administration developed for autonomous vehicles, while advisory and not regulatory, are a first step by a regulator to anticipate rather than respond to system technological changes [39]. However, the guidelines, if anything, are as much a call for research into operator performance with highly automated vehicles (as well as providing general guidance to regulators) as they are guidelines for developers. The implementation of automation to systems with those possessing considerably less operating skill than that of the highly trained operators in sociotechnical systems in which automation has been introduced makes research into these issues particularly critical. In effect, many of the assumptions regarding operator performance with highly automated systems are based on research involving complex sociotechnical systems and not commonly used systems with operators with little training. In sum, the need for research to design automated systems to optimize operator performance with automation is at least as needed now as it was three and a half decades ago, and given the potential import of the introduction of highly automated technology, perhaps even more so.

Today, although technology has increased operational reliability and enhanced operator opportunities to respond to challenging scenarios in system simulators, designers rarely address human considerations in their systems [67], [68]. As a result, the potential for additional automation functionalities to hinder, rather than advance, operational safety remains. Moreover, as noted, sociotechnical system training has tended not to provide operators with the expertise they need to effectively master the capabilities of the automated systems they operate [55]. The resultant automation by expertise by training interaction [53], in which designers provide operators more functionalities than they need for effective system performance, with the inability of designers, managers, regulators, and training personnel to provide training that allows operators to become fully proficient with the automation of the system they operate, has and likely will continue to produce operators with insufficient skills to effectively respond to the full array of automated capabilities in those systems, regardless of the particular system in which the automation has been implemented. This illustrates an irony that could not have been recognized at the time of Ironies of Automation. Not only will operators be in a poor position to respond to automated system anomalies, they will also have difficulties recognizing operating states that had otherwise been routine.

Ultimately, because the Ironies of Automation Bainbridge identified will not be quickly resolved, research is needed to assist designers, managers, regulators, and operators determine how to minimize opportunities for operator errors in automated system interactions. Research, it is hoped, can establish the level of automation functionality operators need to operate particular systems, levels that may well unique to different systems. Operators need only sufficient functionality to effectively operate the particular systems they do during routine and nonroutine operations. Beyond that, additional functionalities should demonstrate their ability to improve operator performance. Requiring operators to master the full range of the technology without adjusting existing training programs to accommodate the additional skills and knowledge they require increases the likelihood that operators will be unprepared to respond effectively to automation-related abnormalities. Designers currently appear to provide functionalities based on technological capabilities and not on operator needs. Once a functionality has been defined, research is needed to develop the training operators will need to effectively operate the systems, through both automated and nonautomated modes, in both routine and nonroutine operating conditions, using the functionalities of the systems. At present, training largely meets either regulator or company requirements, without ensuring that operators can effectively operate the automated technology through all system phases. Unfortunately, little research, which is fundamental to establishing the safety of any system, has been conducted in this field as automated technologies have been increasingly implemented and additional functionalities added without requisite demonstration of their effects on operator performance. Without it however, the ironies of automation can only be expected to increase.

A critical irony of automation, and one underlying those that Bainbridge cited, is that while automation can control routine tasks more reliably and accurately than can human operators, the resultant alteration of the role of the operator and thus the systems he or she operates both enhances and jeopardizes system safety. Bainbridge suggested this as a fundamental irony inherent to automation, but an irony that must be recognized. Failing to address this and the other ironies Bainbridge described in design, training, and operating procedures, has led to accidents. The alteration of the operator's role brought about by automation calls for system designers, trainers, managers and regulators to work together to address the potentially adverse effects of automation.

The extent to which the ironies Bainbridge described will be recognized and addressed in the future is unknown. Perhaps Bainbridge's most significant contribution to our understanding of automation is the recognition and identification of the fundamental effects of automation implementation on operator performance, and their realization in accident occurrences is an unfortunate demonstration of the paper's continued value. Ironies of Automation is a seminal work that has led to a greatly increased understanding of operator interaction with automation, as well as to an improved understanding of operator errors in automated system accidents. Although the ironies of automation that Bainbridge described are unlikely to be resolved in the near future, until they are addressed in design, training, and management, the importance of her work, the need for designers, trainers, managers, and regulators to consider them, will not only continue it will likely increase.

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