MTR190012

MITRE TECHNICAL REPORT

MITRE

Automation in Aviation—Definition of Automation

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January 2019

McLean, VA

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As research related to automation in aviation evolved from human factors to cognitive engineering and from automation to autonomy, a whole generation of research has been forgotten. This series of articles summarizes both the research and the accident analyses conducted from 1970 through 2000. It also provides guidelines for design of automation in aviation. First, what is automation?

Definition of Automation

An early definition of automation in the human factors literature came from Warren (1956). Automation is the "replacement of man by machine or use of machines to control machines" (p. 531). This definition was supplanted by many other definitions in the years to follow. As a result, researchers complained about the lack of a standard definition of automation. As Smith and Dieterly (1980) stated, all definitions were system dependent. Billings (1991a) overcame this problem by introducing the following definition that has since been widely accepted: "Automation is a process that controls a function or task without human intervention."

Automation as a Continuum

An aircraft does not simply have automation or not. For example, Wiener (1987) described a continuum of automation based on the amount of computer monitoring and the amount of computer controlling. Both dimensions go from manual to auto. At the manual level on both, there is high workload and fatigue. On the auto level on both there is boredom, complacency, and erosion of competence. Others have used other dimensions to describe levels of automation. For example, Endsley and Kiris (1995) identified five levels of automation: none, decision support, consensual artificial intelligence (AI), monitored AI, and full automation. In the no automation mode, the human decides and acts while the system does nothing. In the decision support mode, the human still decides and acts but the system suggests. In the consensual AI mode, the human concurs but it is the system that decides and acts. For the monitored AI mode, the system decides and acts but the human can only veto the system's actions. In a fully automated system, the human does nothing while the system decides and acts.

Parasuraman, Sheridan, and Wickens (2000) proposed that automation can be applied to four classes of functions: (1) information acquisition, (2) information analysis, (3) decision and action selection, and (4) action implementation. They also identified 10 levels of automation from high to low (see Table 1). There are aircraft operators who state that there are only three levels of automation in aircraft: (1) manual, specifically, hand flying the aircraft, (2) autopilot engaged and crew using flight guidance for short periods of time, and (3) autopilot with flight management computer engaged for hours at a time (https://youtu.be/pN41LvuSz10).

Table 1. ***Levels of Automation of Decision and Action Selection***
(Parasuraman, Sheridan, & Wickens, 2000, p. 287)

High	10. The computer decides everything, acts autonomously, ignoring the human
	9. informs the human only if it, the computer, decides to
	8. informs the human only if asked or
	7. executes automatically, then necessarily informs the human
	6. allows the human a restricted time to veto before automatic execution, or
	5. executes that suggestion if the human approved, or
	4. suggests one alternative
	3. narrows the selection down to a few, or
	2. The computer offers a complete set of decision/action alternatives, or
Low	1. The computer offers no assistance: human must make all decisions and actions

Human Factors Issues Associated with Automation

Wiener (1987) identified workload and fatigue as the critical problems in systems with no automation. He also identified boredom, complacency, and loss of skills as the critical problems in fully automated systems. In addition, Wiener suggested that poor automation design results in code-induced errors. These errors are cognitive failures due to nonstandard terminology, digit inversion, missing words, and information mismanagement.

Endsley and Kiris (1995), like Wiener before them, found problems with automation. In an analysis looking at the percent of correct responses, they found manual control to have the best performance and full automation the worst (see Figure 1). In addition, Billings (1997) points out, “As software becomes more and more complex, it becomes more and more difficult to verify that it will always function as desired throughout the full operating regime of the aircraft in which it will be placed” (p. 185).

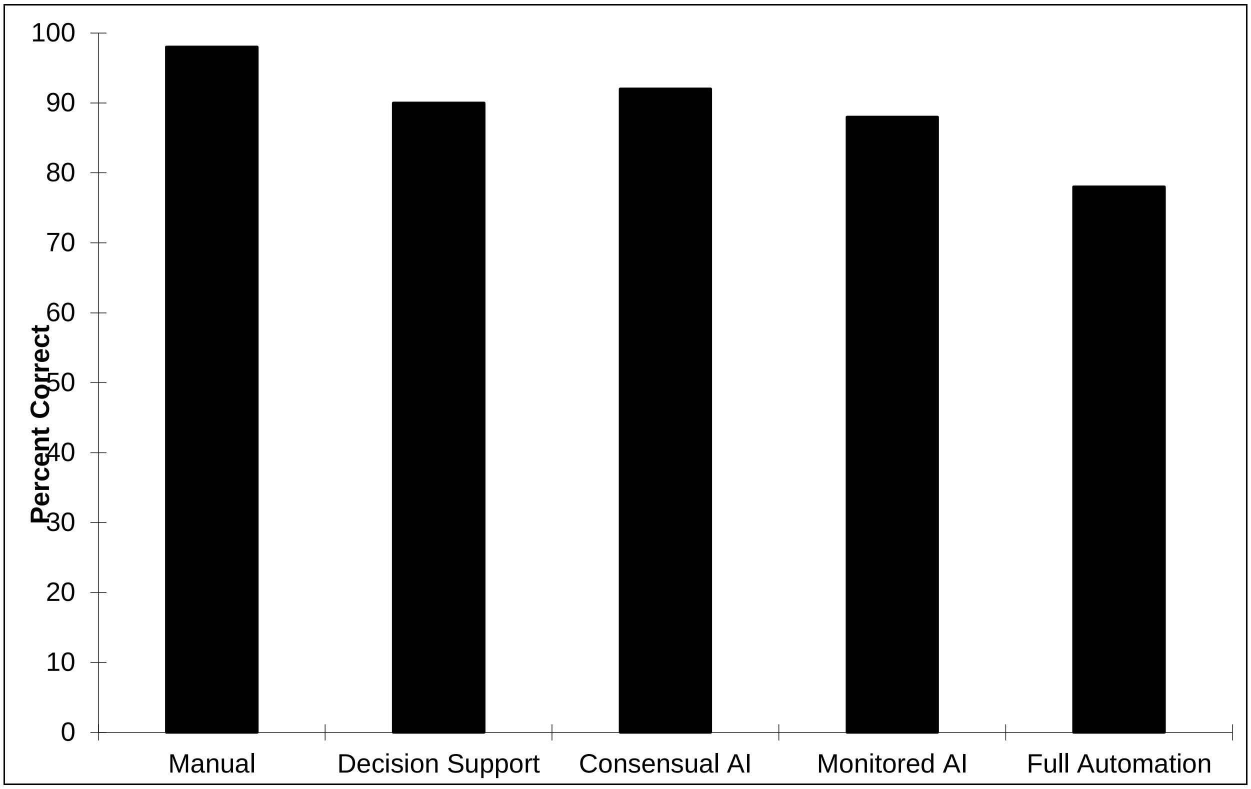

Figure 1. Level of Automation and Control Prior to Automation Failure (Endsley & Kiris, 1995, p. 390)

Research

Research tended to be of two types: comparing with and without automation or comparing varying levels of automation.

Young, Fanjoy, and Suckow (2006) reported that pilots who use automation have a less effective crosscheck and reduced manual flight skills. Their results are based on instructor ratings during simulated flight. The data were from 110 professional pilots with thousands of flight hours. Also, Casner and Schooler (2014) based on a simulator study with 18 airline pilots concluded that when the flight did not include emergency and/or anomalous events, pilots reported a higher percentage of task-unrelated thoughts (21 percent) than when the flight was not as planned (7 percent). The data were collected under two levels of automation. Casner, Geven, Recker, and Schooler (2014) varied the level of automation used by 16 airline pilots in a Boeing 747-400 simulator. They concluded that instrument scan and manual control were retained when automation was used but not cognitive skills. Pilots' navigation performance was rated worse using conventional very high frequency (VHF) omnidirectional range navigation (VOR) than when using the flight management computer. Failure recognition was also worse without the presence of automation in the flight deck.

These authors argued for developing techniques for testing system integrity and immunity to human error. System integrity is critical. As Lagrange (2001) argued, automation makes tasks more complex which in turn makes workload irregular and requires different types of information to be understood by the operator. This information is more abstract, complex, and changes often without operator input. She also introduced the 4CO model: "There will be Cooperation only if there is Confidence, Comprehension prior to this, and therefore Communication from the Outset" (p. 398).

Analysis of Factory Automation Accidents

Although aviation has been a major focus of automation safety, factory automation has also been under scrutiny for decades. In an early study of accidents, Harms-Ringdahl (1985) stated, "Increased automation of machines and equipment means that occupational accident risks are changing. Some dangerous tasks disappear, but new risks may arise" (p. 231). To understand these risks, accident data from the Swedish Occupational Injury Information System were analyzed. Accidents involving a control system were extracted. This resulted in machines with even low levels of automation to be included in the analysis. Of these, 32 percent of the accidents involved presses, 16 percent transportation systems, and 15 percent cutting machines. The frequency of task the operator was performing at the time of the accident is presented in Table 2. Similar data are presented in Harms-Ringdahl (1986).

Table 2. ***Tasks Performed at the Time of the Accident*** **(Harms-Ringdahl, 1985)**

Task	Frequency
Correction of deviation	25
Adjustment	16
Handling of material, normal	10
Changing tool	7
Handling of material, unclear	11
Other	31
TOTAL	100

One quarter of the accidents presented in Table 2 involved correcting deviations. The most common of these was "releasing stuck material" at 7 percent, followed by correcting feed of material" at 5 percent, and "removal of waste material" at 4 percent. The author cited a similar analysis of robot-involved accidents. In these, 60 percent occurred while the operator was correcting a deviation to the robot or the handled material.

Harms-Ringdahl (1985) continued with four case studies: a paper rolling machine, inspection of loading pallets, wrapping of paper rolls, and computer-controlled lathe. From these the author concluded that correcting deviations is hazardous because of poor design and procedures. In some cases, the operators had to develop their own procedure for making the corrections. In all cases the correction had to be made quickly under pressure to keep the production going. This pressure caused operators to perform the task themselves instead of waiting for additional and/or qualified personnel. Also prevalent was the lack of feedback on the status of the automated system. In conclusion, the author recommends "The logic and functions in the control system should facilitate the operator's job, not obstruct it" (p. 236). Further, "provide the operator with sufficient information about system status. If a stop occurs, reasons for that can be valuable. A presentation in words is often superior to coded information" (p. 236). Finally, "Adopt documentation and training to the real tasks of the operator. Start with the main features, not the details." (p. 236).

In a similar study, Karwowski, Rahimi, and Mihaly (1988) compared accident rates before and after implementation of computer automation in an appliance assembly plant. Incidents of dispensary visits increased, especially for operators of the automated equipment. Inflammation of the joints increased 123.6 percent and tennis elbow 47.6 percent. However, fractures were down 39 percent as well as cuts (26.7 percent) and dermatitis (25.3 percent). The greatest change was a 1428.6 percent increase in injuries to the arms above the wrist. Injuries to the legs (88.2 percent) and trunk (74.3 percent) showed large decreases, however. Many types of injuries were down: body motion (100.0 percent), boxes (94.7 percent), particles (92.3 percent), and chemicals (80.3 percent). Large increases were seen in contact by absorption accidents (1542.9 percent), overexertion (680.3 percent), and being struck (92.8 percent). Others were down: contact with toxic substances (98.5 percent), abrasions (94.8 percent), and bodily reaction (85.4 percent). There were also decreases in unsafe acts: improper use of hands (100.0 percent), gripping objects insecurely (100.0 percent), inattentive to footing surface (100.0 percent), failure to use protective equipment (97.9 percent), and failure to secure (94.1 percent).

In a later study, George and Mital (1989) analyzed cases studies in which safety devices were added to automated systems. The cases included a casket manufacturer and a computer manufacturer. Based on these cases George and Mital (1989) identified three categories of automation hazards:

1. "Impact Hazards: Impact hazards are those in which a person may be struck by a moving part of the robot or by parts or tools it is carrying. These hazards are caused primarily by unanticipated movement by the robot and may intensified by speed.
2. Trapping Point Hazards: Trapping point hazards are those in which a person may be trapped between the robot and other fixed objects. Trapping points may also occur as a result of other equipment such as work carriages, pallets or transfer mechanisms working in the robot system.
3. Others: Other hazards included electrical shock, burns, radiation, and so on" (p. 174).

The authors categorize the sources of the hazards as: control errors, unauthorized access, human errors, electric, hydraulic, or pneumatic errors, mechanical hazards, and environmental hazards. They recommend safety devices be tailored to the automated system's use: physical barriers, pressure mats, fences, curtains, chains, sensors, and/or accelerometers may be relevant. They also point out that operators will over rely on maintenance and engineering personnel during the initial startup of the automated system.

Kjellen, Rundmo, Sandetorv, and Sten (1990) concluded from a literature search of accidents in automatic production systems that "the accident frequency rate tends to decrease as a result of automation; the severity of the accidents, on the other hand, tends to increase" (p. 475). The authors argue that the following four characteristics of automation make accident prevention difficult:

1. "Automation leaves the operator in the danger zone without immediate control of the energies of the system. Thus, it is difficult for him to anticipate the possible energy flows. This difficulty is enhanced in systems that utilize exotic chemicals and physical processes.
2. Many automatic plants are characterized by a high-energy build-up and, consequently, by a high potential for severe accidents.
3. Traditional safety measures such as guards are in many cases unfeasible.
4. Automation is often associated with an increased complexity (i.e., systems are made up of networks of closely related subsystems). Accidents tend to occur in interfaces between subsystems and when disturbances progress from one system to another" (pp. 475-476).

Even more recently, Doos, Backstrom, and Samuelsson (1994) analyzed accidents that occurred in automated production. They used data from the mandatory occupational injury reports, follow on investigations, and analysis of the accident as a system deviation. They applied an analysis strategy that placed information into five categories: where and when (e.g., type of production system and shift), important explanatory factors (e.g., how the equipment performed), situational factors (e.g., pace of work), influencing factors (e.g., preventive maintenance), and actions. This strategy was applied to 15 companies that had accidents involving automated production equipment. The companies included automobile manufacturing, iron and steel production, sawmills, food processing, and chemical production. Across these industries 4 to 10 percent of the total accidents involved automation.

In a similar effort, Leverenz and Chadwell (1999) investigated incidents in the petroleum refining industry. They concluded from 136 incidents that one of the main categories was control design, and of this category, lack of feedback was the main cause.

Mineo, Suzuki, Niinomi, Iwatani, and Sekiguichi (2000) analyzed accidents involving factory automation in Japan. They found that many of the accidents were not considered during the design of the system. Examples include workers turning off the power to safety devices, insufficient time margins, or entering caged areas despite warnings. Another part of design that is rarely considered is the procedure to restart the automated system. One example is a set of algorithms that have been developed for starting batch procedures up after an incident (Rouis, 1995).

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