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Automation in Aviation—Guidelines

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Abstract

Objective: Automation has been applied in aircraft since 1891 when Sir Hiram Maxim patented the first stability augmentation system. During the 20th century, automation was applied to almost all aircraft systems. In parallel a rich body of research evolved from 1970 to 2000 to enhance automation's effectiveness as well as to better understand its limitations. The objective of this paper is to summarize that research for current day applications.

Background: Numerous aviation accidents occurred in the period from 1970 to 2000. A series of analyses of these accidents were conducted. From these analyses and the research, guidelines were developed to avoid automation-related issues.

Method: An extensive literature review of both the research and safety analyses was conducted. The focus was on commercial airline aviation.

Results: The research, accident analyses, and guidelines based on the analyses are presented.

Conclusion: Lessons learned in the 20th century were extensive and based upon both research and accident analyses and should be applied to the development of autonomous aviation systems lest we repeat the mistakes of the past.

Keywords: automation, aircraft accidents, accident analysis

Guidelines

Aircraft automation has been around since 1891 when Sir Hiram Maxim patented the first stability augmentation system (Billings, 1996).

Analysis of Commercial Aircraft Automation Design

Taking a very different approach from those above, Edwards (1976) examined automation design not accident or incident data. Based on this examination, Edwards reported the following six problems with the design of aircraft automation:

1. "Unclear philosophies concerning the nature of the optimized man-machine partnership.
2. Flux in the state-of-the-art in control components and techniques.
3. Lack of dissemination of relevant human performance data.
4. Changes in the economic climate and obscurities in the long term predicted environment.
5. A tendency to implement automated sub-systems where implementation is possible irrespective of desirability.
6. Pressure of commercial competition" (p. 14).

When considering the failure alarm system, Edwards (1976) stated that there were two problems: "those concerned with the design features of individual alarms and those concerned with the total integrated alarm system" (p. 21). Edwards also added, "It is important to draw a distinction between reliability in purely engineering terms and the credibility of an alarm" (p. 21). In a later article, Edwards (1977) pointed out that "it must be noted that little or no systematic attempt has been made to design and implement automatic systems in relation to the needs, capabilities, and limitations of human performance" (p. 196). Based on this observation, Edwards came up the following five criteria for choosing automation: (1) engineering feasibility, (2) cost benefit, (3) reliability, (4) accuracy, and (5) commercial competition. Edwards also developed seven questions for designers to ask during development of an automated system:

1. "Are traditional techniques of pilot selection appropriate to the current tasks of manager and monitor?
2. What type of training should be provided?
3. What is the result on the maintenance of skill having only occasional practice at manual control tasks, particularly in the case of the generation of pilots lacking long experience of pre-automatic equipment?
4. Is control performance degraded when the pilot is brought suddenly and unexpectedly into the control loop as a result of equipment failure?
5. Are traditional ideas on flight-time limitation applicable to a job that principally comprises passive monitoring?
6. Are there disadvantages associated with the reduction of the flight-crew to three or even two?
7. How may automatic equipment best be interfaced with the crew?" (Pages 96 – 197).

Vakil and Hansman (2000) took a very different approach to examine automation related accidents. They applied cyclomatic complexity analysis to the design of automation in a wide range of aircraft. This is an analysis tool used extensively in computer science. It counts the number of linearly independent paths through a program. In this case, it was used to count the number of paths through automated systems in the B727, B747, B757, and B777. Mode transitions had extremely high cyclomatic complexity. In addition, the authors developed a Web-based Pilot Automation Complexity Survey. Eighty-nine commercial transport pilots and four military pilots completed the survey. Total flight hours varied between 150 and 27,500 with an average of 10,250. The mode transitions that had extremely high cyclomatic complexity were those that the pilots identified as problematic.

Based on both the analysis and the survey, the authors identified the following auto flight system issues: First the limitations of the physical system (e.g., engine spool up time) can be hidden by the automation making it difficult for pilots to understand the current system status. Alerts are designed into an automated system only for identified specific failures. But designers are not omniscient. The wind shear warning is suppressed for seven seconds as the flaps are being deployed on a DC-9. An aircraft crashed at the Charlotte airport on 2 July 1994 when severe wind shear was experienced at 275 feet when the flaps were being deployed.

The second system issue was representation. There are often disconnects in the representation of the design model (i.e., the designer's conceptual model of the system developed during the design of the system), the user's model (i.e., "a mental representation created by the user through interaction with the actual system" p. 116), and the system image (i.e., "the instantiation of the actual physical object and includes the documentation, instructions, labels, and so on" p. 116). These differences in representations can lead to accidents. For example, in the A320 accident at Nagoya, the pilots inadvertently put the aircraft in a go-around mode. In this mode, the aircraft is automatically trimmed to climb. The pilots, believing they had totally disengaged the go-around, tried to push the nose down to approach the airport. Instead the aircraft continued to pitch up until it stalled and crashed.

The third system issue identified was the lack of appropriate and observable feedback. On 20 January 1992, an A320 crashed during approach into Strasbourg, France. The crew had placed the aircraft in an incorrect descent mode: a vertical speed mode of 3,300 feet per minute rather than a flight path angle of 3.3 degrees. The displays look very similar. The pilots did not recognize the problem in time.

Finally, the Flight Deck Automation Working Group (2013) identified the following vulnerabilities with automated systems on the flight deck:

- "Pilots sometimes rely too much on automated systems and may be reluctant to intervene;
- Autopilot mode confusion errors continue to occur;
- The use of information automation is increasing, including implementation that may result in errors and confusion; and
- FMS [Flight Management System] programming and usage errors continue to occur" (p. 32).

Human Factors Checklist

Although approximately 60 percent of all aviation accidents have been attributed to pilot error,[1] there has been no standard method for investigating the human factors aspects of these accidents.

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[1] http://www.planecrashinfo.com/cause.htm

This is especially critical in accidents involving automation. To remedy this situation, Feggetter (1982) developed a checklist. It has been used to this day. It provides categories of human factors that must be considered during accident investigation and conversely during design of automated systems. The checklist is presented in Table 1.

Table 1. ***Human Factors Checklist***
(Feggetter, 1982, pp. 1071-1072)

Heading	Comment
Cognitive System	
(1) Human information processing system	
Senses	Check within sensory limits
Perception	Check order of reception of information
Attention	Check distraction
Memory	Check frequency of events
Decision	
Action	
Monitoring	
Feedback	
(2) Visual illusions	Likely conditions
	Refraction
	Fog
	Ground texture
	Auto kinetic
(3) False hypothesis	Likely conditions:
	Expectancy high
	Attention elsewhere under stress
	After high concentration
(4) Habits	Previous experience
	Positive and negative transfer
(5) Motivation	Arousal levels high/low
	Real objective of pilot
(6) Training	Check experience, skills
(7) Personality	Check interaction with:
	Colleagues/family
	Attitudes to job
	Self-awareness/ambitions
(8) Fear	Military mission
Social System	

Heading	Comment
(9) Social pressure	Pressures from crew, trans cockpit gradient, passengers/company
(10) Role	Role conflict (manhood versus safety)
(11) Life stress	Based on life experiences survey … including death of a relative, divorce, marriage, etc.
Situational System	
(12) Physical stress	
Physical condition	
State of nutrition	Food and water
Drugs	History of medication
Smoking	
Alcohol	
Fatigue	Work rest cycle/duty times activities in preceding 48 hours and earlier where appropriate
Sleep loss	
(13) Environmental stress	
Altitude	
Speed/motion	
Visual	
Glare	
Disorientation	
Temperature	
Lighting levels	
Noise	
Vibration	
(14) Ergonomic aspects	
Design of controls	Check stereotype responses
Design of displays	Compatibility
Seating	
Presentation of material	Check ambiguities of:
	Labeling legibilities
	Position of information
	Text layout
Policy for dealing with emergencies	

Toola (1992, 1993) presented a similar checklist for evaluating process automation. The emphasis on information is also not new. As Sarter (1996) states the early concerns regarding automation were questions of quantity: how much will automation reduce pilot workload; how much training does it require; and how much information should be presented to the pilots? Experience indicated that quantity was not as important as quality: what kind of automation is needed? Similarly, there was a shift in looking at the performance of an individual crewmember to the performance of the entire crew.

Survey of Pilots

Taking another approach, several researchers used only surveys to identify automation concerns. In the first, Lauber (1979) reported the results of interviews with airline pilots. These pilots identified the following problems which are exacerbated in highly automated flight decks: (1) preoccupation with minor mechanical problems, (2) inadequate leadership, (3) failure to delegate tasks and assign responsibilities, (4) failure to set priorities, (5) inadequate monitoring, (6) failure to use available data, and (7) failure to communicate intent and plans.

In a more recent survey of pilots conducted by the Australian Transport and Regional Development Department's Bureau of Air Safety Investigation, pilots reported that the level of automation in aircraft was not excessive. Their responses to "They've gone too far with automation" are presented in Figure 1. First officers were more likely to endorse automation than captains especially in emergency situations. They did identify the following problems, however: (1) difficulty with mode selection, (2) difficulty with mode awareness, (3) being unaware of what the autopilot was doing, (4) lack of adequate feedback, (5) lack of complete knowledge on how the automation works, (6) need for workarounds (i.e., intentionally incorrect or fictitious data) to ensure the automation is doing what they want it to do, and (7) falling asleep due to boredom Bureau of Air Safety Investigation (1998).

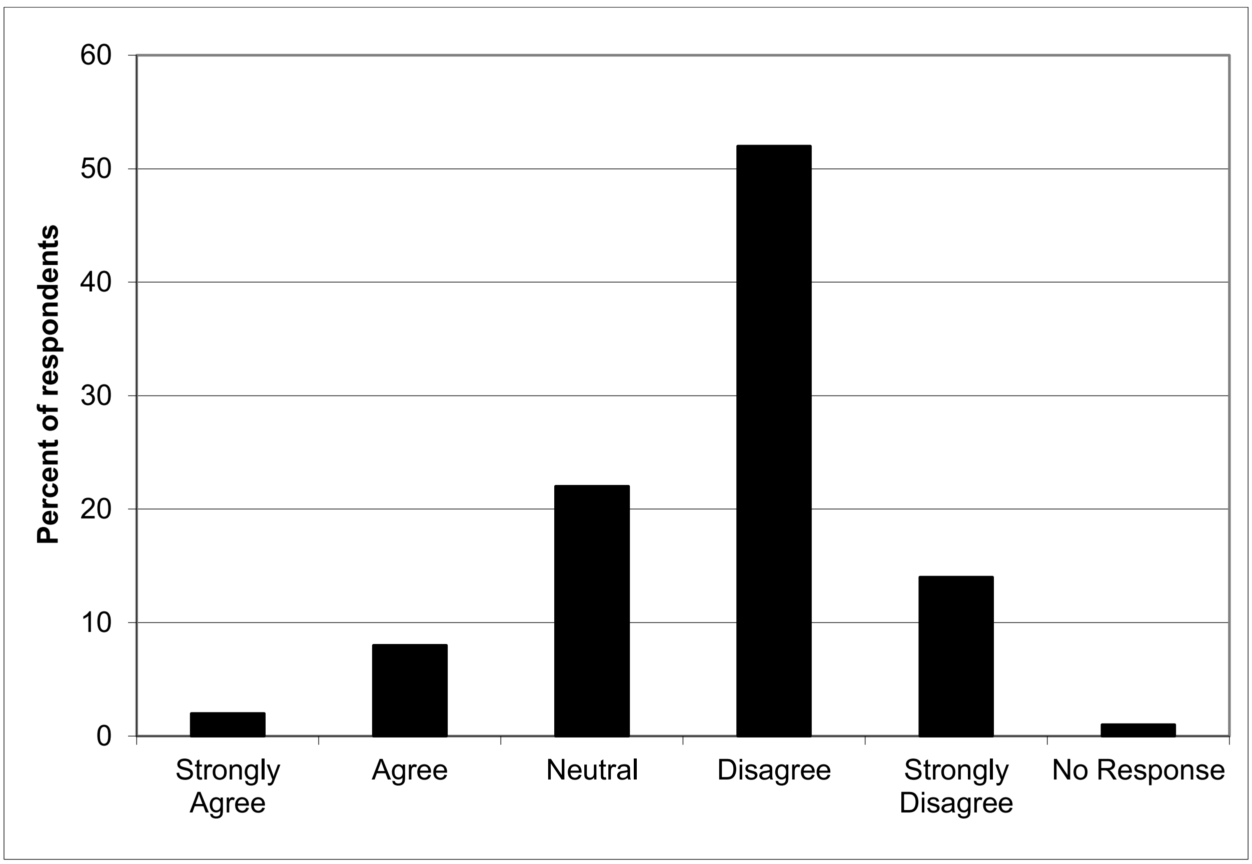

Figure 1. Response to "They've gone too far with automation" (Phillips, 1999)

Kludze (2001) did a similar survey of engineers in the automobile, nuclear, power, and airline industries asking for lessons learned to apply to spacecraft mission operations. The major concerns identified in the survey were knowledge atrophy, redistribution of costs (robbing Peter to pay Paul), and loss of experienced personnel.

Benefits of Automation

Although the previous section paints a poor picture of automation, it does have many benefits. First it reduces workload. For example, Ekstrom (1962) reported the results from two pilots flying in a six degree of freedom simulator that more automation can reduce workload. The comparison was between a minimum flight system that provided stability augmentation in three axes with a piloted flight system that provided control stick steering and hold modes for angle of attack, attitude, bank angle, or heading angle. Workload was inferred from performance of a visual reaction time secondary task. The highest workloads, however, occurred at transitions between mission phases.

In a later review, Boehm-Davis, Curry, Wiener, and Harrison (1981) identified two benefits of automation on flight decks. First, automation enables performance of tasks that humans could not perform because of cost, time, or safety. An example is performing anti-collision maneuvers at close quarters. Second, automation can provide a better solution to a problem than humans. An example is fuel management. As Whitaker (1981) stated, “Electronics can advise the pilot, or fly the aircraft for him, saving fuel in four ways: operating the throttles to give the optimum engine conditions, giving the pilot an area-navigation facility to allow him to fly direct routes, controlling the fuel flow, and through active controls” (p. 563).

Wiener and Curry (1980c) identified the following advantages of automation: (1) increased capacity and production, (2) decreased manual workload and fatigue, (3) relief from routine operations, (4) relief from small errors, (5) more precise handling of routine operations, (6) economical utilization of machines, and (7) damping of individual differences. Billings (1997) used more global terms in stating that the benefits of aviation automation are safety, reliability, economy, and comfort.

There may be even greater benefits associated with more advanced automation designs. For example, Parasuraman, Hilburn, Molloy, and Singh (1991) reported that adaptive automation (i.e., changing the level of automation in relation to operator workload) enhanced performance. The tasks were tracking, monitoring, and fuel management. However, the enhancement was significant only during the early trials and decreased over time. There were no indications of automation costs with the adaptive automation. The subjects were 24 undergraduate students. Scerbo (1999) also examined adaptive technology but for compensating for decrements in human performance in thermal environments.

Automation benefits are not limited to aviation but to every automation application. For example, Rudisill (2000) identified the benefits of automation for space transportation systems: (1) economic efficiencies, (2) enhanced precision, (3) enhanced safety, (4) economy of cockpit space and enhanced information display, and (5) reduced workload.

Some system designers have seen automation as a panacea for all their design problems. For example, automation promised to reduce operator workload. However, Ephrath (1980) found that autopilots did not minimize pilot workload at touchdowns below the level of workload in the manual mode. Further, automation should speed system responses. But Stewart (1978), comparing the performance speed of military intelligence analysts using automated or manualfiling systems, found no improvement in performance speed associated with automation (although he did find improvements in accuracy).

Others have concentrated on the problems. For example, Wiener and Curry (1980a) listed several problems with automation including: (1) automation-induced errors, (2) equipment set-up errors, (3) false alarms, and (4) loss of operator proficiency in the manual mode.

Automation may actually be a Pandora’s box. More must be known about human performance in automated systems before this technology can be optimally applied. Automation has been used to enhance safety, increase productivity, reduce operator workload, and minimize error. But along with its many benefits have come problems. One of the most serious is a system failure that forces the operator (or user) to suddenly and unexpectedly enter the control loop. The operator, who has learned to rely on the automated system for crucial decision-making, must first detect the system failure, understand the current context and its implications, and then take the steps necessary to recover. In some systems (e.g., aircraft, air traffic control, nuclear power plants), the operator must not only act, but act quickly, accurately, and confidently, since recovery time may be critical.

References

Billings, C. E. (1997). *Aviation Automation: The search for a human-centered approach.* Mahwah, New Jersey: Lawrence Erlbaum Associates.

Billings, C. E. (February 1996). *Human-centered aviation automation: principles and guidelines.* NASA Technical Memorandum 110381, Moffett Field, California: NASA Ames.

Boehm-Davis, D. A., Curry, R. E., Wiener, E. L., & Harrison, R. L. (January 1981). *Human factors of flight-deck automation – NASA/Industry Workshop* (NASA-TM-81260). Moffett Field, California: NASA Ames Research Center.

Bureau of Air Safety Investigation Advanced technology aircraft safety survey report. (1998) http://www.atsb.gov.au/aviation/pdf/advtek.pdf

Edwards, E. (1977). Automation in civil transport aircraft. *Applied Ergonomics, 8,* 194–198.

Edwards, E. (1976). Some aspects of automation in civil transport aircraft. In T. B. Sheridan & G. Johannsen (Eds.), *Monitoring behavior and supervisory control.* New York, New York: Plenum.

Ekstrom, P. J. (1962). *Analysis of pilot workloads in flight control systems with different degrees of automation.* Paper presented at Institute of Radio Engineers International Congress, Long Beach, California: Human Factors Engineering in Electronics.

Ephrath, A. R. (1980). Pilot workload during an instrument approach. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-10(10)* 676–678.

Feggetter, (1982). A. J. A method for investigating human factor aspects of aircraft accidents and incidents. *Ergonomics, 25(11),* 1065–1075.

Flight Deck Automation Working Group, Aviation Rulemaking Committee/Commercial Aviation Safety Team. (September 5, 2013). Operational Use of Flight path Management Systems.

Kludze, A. K. (2001). Spacecraft mission operations – lessons learned from automation. 20th D*igital Avionics Systems Conference, 1,* 4.A.4-1–4.A.4-5.

Lauber, J. K. (1979). *Resource management on the flight deck: Background and statement of the problem,* (pp. 3–16). Proceedings of a NASA/Industry Workshop on Resource Management on the Flight Deck, NASA Conference Publication 2120.

Parasuraman, R., Hilburn, B., Molloy, R., & Singh, I. (October 1991). *Adaptive automation and human performance: III. Effects of practice on the benefits and costs of automation shifts* (NAWCADWAR-92037-60). Warminster, Pennsylvania: Naval Air Warfare Center.

Phillips, E. H. (November 22, 1999). Survey revealed automated cockpits harbor safety pitfalls. *Aviation Week and Space Technology, 151(21),* 48.

Rudisill, M. (2000). *Crew/automation interaction in space transportation systems: Lessons learned from the Glass Cockpit.* Proceedings of the Human Space Transportation and Exploration Workshop.

Sarter, N. B. (1996). Cockpit automation: from quantity to quality, from individual pilot to multiple agents. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: theory and applications,* (pp. 267–280). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Scerbo, M. W. (1999). *Adaptive automation: Who can you turn to when things heat up* (AIAA-99-3503). Proceedings of the 33rd Thermophysics Conference, American Institute of Aeronautics and Astronautics.

Stewart, S. R. (September 1978). *Utility of automation of order of battle and target intelligence data for intelligence analysis* (ARI-RR-1194). Alexandria, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences.

Toola, A. (1993). The safety of process automation. *Automatica, 29(2),* 541–548.
Toola, A. (1992). Elicitation of safety requirements for process automation. *Reliability Engineering and System Safety, 35,* 209–215.
Vakil, S. S. & Hansman, R. J. (May 2000). *Analysis of complexity evolution management and human performance issues in commercial aircraft automation systems* (ICAT-2000-3). Cambridge, Massachusetts: International Center for Air Transportation, Massachusetts Institute of Technology.
Whitaker, R. (February 28, 1981). Fuel savers in the cockpit. *Flight International,* 563–568.
Wiener, E. I. & Curry, R. E. (1980a). *Automation in the cockpit,* (p. 38). Proceedings of the Human Factors Society 24th Annual Meeting.
Wiener, E. L. & Curry, R. E. (June 1980c). *Flight-deck automation: Promises and problems* (NASA-TM-81206). Moffett Field, California: NASA Ames Research Center.