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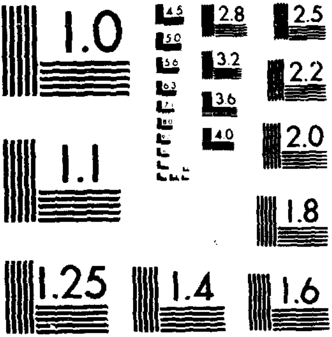

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# FLIGHT-DECK AUTOMATION: PROMISES AND PROBLEMS

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## Summary

Modern microprocessor technology and display systems make it entirely feasible to automate many flight-deck functions previously performed manually. There are many real benefits to be derived from automation; the question today is not whether a function can be automated, but whether it should be, due to the various human factor questions that are raised. It is highly questionable whether total system safety is always enhanced by allocating functions to automatic devices rather than human operators, and there is some reason to believe that flight-deck automation may have already passed the point of optimality. This is an age-old question in the human factors profession, and there are few guidelines available to the system designer.

This paper presents the state of the art in human factors in flight-deck automation, identifies a number of critical problem areas, and offers broad design guidelines. Some automation-related aircraft accidents and incidents are discussed as examples of human factors problems in automated flight.

## 1. Introduction

Papers of this sort often begin with the almost mandatory statement that in future systems automatic devices will provide for the real-time, moment-to-moment control of the process, and that the human operator will be relegated to the post of monitor and decisionmaker, keeping watch for deviations and failures, and taking over when necessary (see numerous papers in Sheridan and Johannsen 1976). This prescription is based on the observation that inanimate control devices are extremely good at real-time control, but must be backed up by the remarkable flexibility of the human as a supervisor and standby controller, in case of breakdown or other unforeseen events.

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Another virtually mandatory statement is that the human, for all his putative flexibility, is not so good at the monitoring task and is highly likely to miss critical signals, as well as to make occasional commissive errors. Indeed, the verity of the second statement, supported by endless accident and incident reports, tempts designers to "automate human error out of the system." The lure is especially great in aviation, where the cost of human failure can be so catastrophic.

Although the authors have no quarrel with the two basic statements, the assumption that automation can eliminate human error must be questioned. This paper will explore automation of flight-deck functions, the presumed benefits and possible pitfalls, and will ask whether it is possible that cockpit automation may have already passed its point of optimality. This examination is made more urgent by rapid developments in microprocessor technology and many present and near-future applications in the cockpit (Lovesey 1977; Ropelewski 1979). The question is no longer whether one or another function can be automated but, rather, whether it should be.

Much of what will be said about automation on the flight deck may be applied equally well to other large-scale systems (e.g., air traffic control and nuclear power generation), and we invite the reader to do so. Likewise, much of what has been written about automation in other fields could apply to the flight deck; for example, note the many excellent papers on process control appearing in Edwards and Lees (1974) and the overview by Shackel (1967).

The very word "automation" is likely to conjure up, at least in the mind of the technologically unsophisticated, two rather opposite images, both of which can ultimately be shown to be exaggerated, if not incorrect. On the negative side, automation is seen as a collection of tyrannical, self-serving machines, degrading humans, reducing the work force, bringing wholesale unemployment, and, perhaps even worse, offering an invitation to a technological dictator to sieze power and build a society run by Dr. Strangeloves, aided by opportunistic, cold-hearted computer geniuses. The classic Charlie Chaplin movie Modern Times depicted the subjugation of industrial man to machine, and more recently the popular novels and movies by Michael Crichton (Westworld, Terminal Man) dwelled on the perils of a computer-based society gone awry. So far, there is no indication that such a thing has happened, or that it will.

Perhaps equally fallacious is the positive image of automation: quiet, unerring, efficient, totally dependable machines, the servant of man, eliminating all human error, and offering a safe and cost-effective alternative to human frailty and caprice. The traditional dream of traditional engineers has been to solve the problem of human error by eliminating its source. It is worth noting that the general public appears as skeptical of the infallibility of automation as they are fearful of its consequences. Witness the endless popular jokes about the announcement over the airliner intercom that the plane is being flown entirely by automatic devices.

Thus, the authors will shortly present what is popularly called "the good news and the bad news" of flight-deck automation, for there are ample instances of each. We shall finally attempt to provide some tentative guidelines to the implementation of automatic devices in aircraft. Automation of human functions in air traffic control (ATC), weather forecasting, dispatching, and maintenance, although vitally important, will not be addressed.

## 2. Why automate?

It is trite (though necessary) to say that automation may be a mixed blessing in the cockpit. Already there is serious concern about the effect of automation on flight-deck performance, workload, and, ultimately, on aviation safety (Edwards 1976, 1977). Questions have arisen from accident reports, incident reports (such as NASA's Aviation Safety Reporting System). airline training, simulator studies, and our own interviews with crewmembers and airline flight managers about such matters as failure detection, manual takeover, skills degradation, and even job satisfaction and self-concept of pilots and flight engineers operating highly automated equipment. These are not new problems, but they are now being addressed with a new urgency and frankness, impelled by the technological developments that make flight-deck automation entirely feasible, at least from an electromechanical point of view.

### 2.1 A basic assumption

One hears, from time to time, talk of the unmanned airline cockpit. Although the authors find this neither unthinkable or technologically infeasible, we feel that as far into the future as we can see, it would be socially and politically unacceptable. Therefore, while we do not completely dismiss the idea of an unmanned airliner, this discussion is based on the assumption that airliners will carry a human crew. For a concurring view, see McLucus (1978). Questions about the size, functions, selection, training, and motivation of this crew, however, remain open. It should be noted that even the unmanned factory, so often predicted, has never come to pass (de Jong and Koster 1974).

### 2.2 Driving forces

Before going further, one should ask just what is the thrust behind cockpit automation. We have identified three factors.

2.2.1. Technology: The explosive growth of microprocessor technology has already been mentioned. Rapid improvement in performance and decrease in size, cost, and power consumption of various electronic devices, sensors, and display media, make automation of many flight-deck (as well as ground-based) systems a reasonable alternative to traditional manual operation. This trend will continue well into the next century. One should note that technology is not a goal (as the next two factors are), but is instead a facilitating factor.

2.2.2. Safety: More than half of the aircraft accidents are attributed to "human error." This term can be somewhat misleading, as one is never sure whether it means cockpit crew error or includes other humans, such as ATC controllers, weather forecasters, maintenance personnel, and dispatchers. Be that as it may, there exists ample need to reduce human error in the cockpit. Autopilots, flight directors, and alerting and warning systems are examples of automatic systems that have had a beneficial effect on pilot workload and on safety margins. The ground proximity warning system (GPWS) provides an excellent example. Since its introduction by Congressional mandate in 1974, there has been a dramatic reduction in terrain-strike accidents, both in the United States and worldwide. It is impossible to know how many aircraft and lives have been saved by this device. Nonetheless, it is often denounced by pilots for the frequent false alarms it generates. These false alarms are annoying and potentially dangerous, but on balance, the GPWS would have to be viewed very favorably.

2.2.3. Economics: Undoubtedly, automation can bring about enormous savings through fuel conservation, if total flight time can be reduced and if more fuel-efficient climb and descent patterns can be implemented (Curry 1979; Feazel 1980). Both the potential for dollar savings and the effect on airline profits are difficult to exaggerate, especially in the face of steadily rising fuel prices. In 1978 a gallon of jet fuel sold for about 38 cents (U.S.), for 70 cents by the end of 1979, and is forecast to be more than one dollar by the end of 1980. A recent analysis of the operating costs and profits of a major U.S. carrier showed that a 3% savings in jet fuel could result in a 23% increase in profits. Automation in both ATC and the cockpit could easily produce the 3% reduction in fuel consumption; even greater savings are possible on shorter runs, such as the New York to Boston shuttle. Potter (1980) reported that every percentage point increase in jet fuel price will cost Western Airlines $4,000,000. Likewise, we presume, every percentage point by which consumption can be reduced should save the company about the same amount. Finally, Covey et al. (1979), who summarized 12 fuel conservation methods, have concluded that a savings of up to 12% could be realized from their optimal use. Five percent savings have already resulted from a partial implementation. Most of the methods they outlined would require automation to some degree in order to achieve maximum savings.

As in other industries, a large component of airline operating costs is labor. Although it is questionable whether automation can reduce the number of persons in the cockpit (the authors do not wish to plunge into the two-versus-three person crew controversy at this time), it is a possibility that should not be totally discounted (O'Lone 1980).

Furthermore, automation may reduce direct labor costs somewhat by reducing flight times through more efficient lateral navigation, and may cut maintenance costs by more effective use of the equipment. In considering economics, however, one must also recognize that automation equipment is expensive. The airline industry will incur enormous capital costs to acquire the equipment, as well as operating costs for training and maintenance. But even putting the safety question aside and looking only at the economics, it appears at this time that flight-deck automation should be a very good investment, especially in view of continuing fuel price increases and possible shortages.

## 3. Representative aviation accidents and incidents

So much for the promises of flight-deck automation. Let us now examine some of the problems, which can best be illustrated by representative aviation accidents and incidents. These accounts are confined, by necessity, to very brief summaries and comments on what is usually a very complex causative chain. We do not wish to oversimplify either the facts or the causative interpretations of these accidents, and the interested reader is encouraged to read the full reports. For other examples, see Rolfe 1972, Danaher 1980, and Wiener 1977 and 1980.

### 3.1 Failure of automatic equipment

One of the concerns regarding the use of equipment for automatic control or monitoring is that it may fail to operate correctly. Consider the following incidents reported in a cockpit newsletter:

1. In an approach with the autopilot in control, a bend in the glidepath at 500 ft above the ground caused a very marked pitch down, resulting in excessive sink rate. The pilot, though fully aware of the situation, did not react until his position was so critical that a very low pull-up had to be made.

2. The altitude preselect (a device to level the aircraft at a predetermined altitude) malfunctioned. This went unnoticed by the pilots and an excessive undershoot was made (descent below desired altitude).

3. At level-off by use of the altitude preselect and with the throttles in idle (was autothrottle in use or expected?), the speed dropped close to the stall point before this condition was detected and rectified by power application.

4. While in navigation mode (autopilot steering the aircraft to maintain a track over the ground), the aircraft turned the wrong way over a checkpoint. Although the wrong turn was immediately noticed, the aircraft turned more than 45° before the pilot took action.

These reports are brief, and the present authors do not have access to more details. Thus it is difficult to determine how much of the fault should be attributed to hardware failure, improper setup of the equipment, and inappropriate expectations of how the equipment should operate. Nonetheless, the reports are typical of the day-to-day problems encountered by flightcrews.

## 3.2 Automation-induced error compounded by crew error

The following accident illustrates one of the special hazards of automation, one that many traditional engineers might rather not hear about. In this case, the causative chain of events was set into motion by the failure of the automated equipment; the equipment error was then compounded by crew error, and a crash resulted (NTSB, 1979a). A Swift Aire Lines Nord 262 departed Los Angeles International westbound. Shortly after gear retraction, its right engine autofeathered. Autofeather is a device common on advanced twin-engine propeller-driven planes. It senses a loss of power in an engine and feathers the propeller automatically. It is armed only on takeoff and initial climbout. The purpose of the autofeather is to preclude the possibility that a crewmember will shut down the wrong engine in the event of power failure on takeoff. It remains for the crew to secure the dead engine, increase power on the operating engine, make trim and control adjustments, and continue climbing to a safe altitude for return to the field.

Immediately after the right engine autofeathered, the crew shut down the <u>left</u> (operating) engine; the result was a fatal ditching in the Pacific Ocean. Examination of the right engine showed there had been no power loss, and the autofeather had been due to a broken hydraulic hose in the sensing mechanism. Later investigation revealed that inadvertent autofeathers on Nord 262 aircraft were not unusual. Thus, a device designed to automate human error out of the system had triggered a chain of events that was compounded by the very human error it was supposed to prevent.

## 3.3 Crew error in equipment setup

Inertial navigation systems (INS) are automatic navigators. They are also used to supply automatic pilots with position information to allow control of aircraft track (the navigation mode). A series of checkpoints, or waypoints, defining the desired track across the earth, is loaded into the INS computer by keyboard before the flight by entering the waypoint latitude and longitude. The inertial navigation system aligns itself before flight and knows its accuracy status; since the accuracy increases during alignment, the INS will be less tolerant of errors in initial position. During the initial alignment, one crew loaded their position as a northern latitude rather than the actual southern latitude. The error was not detected by either the INS or the crew until after takeoff. The aircraft had to return to the departure point because the INS could not be reset in flight.

## 3.4 Crew response to a false alarm

Another form of automation-induced error is the false alarm, which persuades the crew to take corrective action when, in fact, nothing is wrong with the system (other than the spurious alarm). Such an error occurred during the takeoff of a Texas International DC-9 from Denver (NTSB, 1977). As the aircraft accelerated to the velocity of rotation (where the nose wheel is lifted off the runway and the aircraft assumes a nose-high pitch attitude), about 150 knots in this case, the stall warning actuated. This was a "stick shaker," a tactile warning system whereby the control column begins to shake, as well as to give auditory "clacks." Believing that a stall was imminent, in spite of normal airspeed and pitch attitude indications, the crew elected to abort the takeoff, resulting in a runway overrun, severe damage to the aircraft, and nonfatal injuries to some passengers. Interestingly, the pilots had both experienced spurious stall warnings on takeoff previously, but they probably had little choice but to regard this as a bona fide alert.

In a "split second" the crew faced a choice between aborting the takeoff, with an almost inevitable, though perhaps noncatastrophic, accident, and continuing the takeoff with a plane that might not be flyable, which could result in a much worse accident. It might be interesting, but perhaps not highly profitable, to speculate on what might have occurred if this decision function had been automated. Suffice it to say that the decision to stop or go, as it faced the crew at that critical moment during rotation, would have been in the hands of some distant software designer. We leave it to the reader to decide if that is a comforting thought.

## 3.5 Failure to heed automatic alarm

An airline aircraft was on an approach to landing, but at an excessive airspeed. During the approach the ground proximity warning system was triggered three times (once for excessive descent rate, twice for less than 26° flaps with gear extended and excessive descent rates). Instead of executing a missed approach, the captain continued toward landing, crossing the runway threshold at a speed of 184 knots, 61 knots above the reference speed. The aircraft landed approximately halfway down the runway and overran the far end; one person was injured seriously.

The National Transportation Safety Board (179b) determined that the probable cause of the accident was the captain's complete lack of awareness of airspeed, vertical speed, and aircraft performance throughout the approach and landing. A contributing factor was the copilot's failure to provide required callouts of airspeed and vertical speed deviations. In its analysis, the NTSB did note that the GPWS alerts should have indicated to the crew that the approach was improper and that a missed approach was necessary. It also mentioned that none of the alerts caused the crew to take corrective action, even though company procedures dictated that they should do so.

## 3.6 Failure to monitor

This type of problem can be exemplified by certain "controlled flight into terrain" accidents, in which a flightcrew, with the aircraft totally under control, flies it into the ground (or water), usually without any prior awareness of impending disaster (see Ruffell Smith 1968; Wiener 1977). In December 1972, an Eastern Airlines L-1011 was approaching Miami on a clear night. During the prelanding cockpit check, the crew encountered an unsafe landing gear indication (light failed to illuminate). ATC assigned the aircraft to a westward heading at 2000 ft (mean sea level), while the crew attempted to diagnose the problem. The plane was under autopilot control. The flight crew became preoccupied with the problem at hand (the captain and first officer had pulled the bulb appliance out to check the lamp and were having trouble putting it back together). They did not notice that the autopilot had disengaged and that the aircraft was in a slow descending spiral. They flew into the ground, having never detected their departure from altitude. even with full cockpit instrumentation, extra-cockpit vision, a C-chime altitude alert that sounded (and was present on the cockpit voice recorder), and an ambiguous inquiry from a radar operator in Miami who observed the descent on he alphanumeric readout on his set (NTSB, 1973).

## 3.7 Loss of proficiency

One of the most easily imagined consequences of automation is a loss of proficiency by the operator. Although there has been no specific accident or incident in which such loss of flying proficiency has been cited as a contributing factor, individuals involved with pilot training have noted perceptible skill losses in pilots who use automatic equipment extensively. For example, copilots on wide body jets, which have sophisticated automatic systems, accrue enough seniority to become captains on narrow body jets, which do not have sophisticated autopilot-autothrottle systems. Those who report these skill losses go on to say that they feel they have resolved the problem by asking copilots to turn off the automatic systems prior to transition training so that they regain proficiency with manual systems. We have noticed that many crewmembers seem to have discovered this on their own and regularly turn off the autopilot, in order to retain their manual flying skills.

Beyond the possible loss of proficiency, a change in attitude may be induced by use of automation. The following excerpt from a letter written by a flight training manager speaks succinctly of the issue:

> Having been actively involved in all areas of this training, one disturbing side effect of automation has appeared, i.e., a tendency to breed inactivity or complacency.
>
> For example, good conscientious First Officers (above average) with as little as 8-9 months on the highly sophisticated and automated L-1011s have displayed this inactivity or complacency on reverting to the B-707 for initial command training.
>
> This problem has caused us to review and increase our command training time for such First Officers. In fact, we have doubled their allotted enroute training time.

## 4. Common problem areas

The previous discussions have concerned some very specific problems with the use of automated devices. We have analyzed the above incidents and many others and have tried to rephrase the problem statement into a more general context. Hopefully, this will assist interested parties from diverse disciplines and industries to communicate in a more effective manner. Five general problem areas are described below with some of the major issues outlined for each. As is to be expected, the boundaries of the problem areas are somewhat ill-defined, and many questions may legitimately belong to more than one category.

### 4.1 Automation of control tasks

This problem area has received the most attention in the past. When control tasks are automated, the operator's role becomes one of a monitor and supervisor; hence, the primary issues revolve around his ability to perform these functions, since the control task is almost always accomplished satisfactorily by the automatic system. Typical questions to be examined are:

1. Under that conditions will the human acting as a monitor be a better (or worse) failure detector than the human as an active controller-operator?

2. Is there a significant "warmup" delay when the human transitions from passive monitor to active controller? Does automation lull the operators into a state of low alertness or do they enter a state in which they are easily distracted from the monitoring task by unimportant events?

3. What should be the form of the interaction between the operator and the automatic system? If the automatic system is changing the system configuration, should it make the change automatically and inform the operator, or make the change only after operator acknowledgment? Should it tell the operator why it is making the change or not?

4. What is the effect of different levels of equipment reliability on the operator's ability to detect, diagnose, and treat malfunctions in manual and automatic tasks? It seems plausible that equipment reliability could be an important factor. For example, if the equipment is very unreliable, then the operators will be expecting malfunctions and will be adept at handling them. If the equipment is very reliable, then there is little need for failure detection and diagnosis on the part of the operator. An intermediate level of reliability, however, may be quite insidious since it will induce an impression of high reliability, and the operator may not be able to handle the failure when it occurs.

## 4.2 Acquisition and retention of skills

The use of automation will probably result in a decrease in the skill level for well-learned manual tasks. Of practical importance is the rate at which these skills deteriorate and the countermeasures available to prevent unacceptable skill loss. On the other hand, the training literature suggests that part-task operation (with the other tasks automated) during the early, familiarization phases of operation may be an effective means of total acquisition of operational skill. Thus, the major unanswered questions regarding the initial acquisition, reacquisition, and retention of skills are as follows:

1. How quickly do manual skills deteriorate with lack of use? What factors influence the rate of loss?

2. Can periodic practice prevent skill deterioration? If so, what frequency is required?

3. Are there alternatives for practice with the actual system, for example, part-task simulators?

4. What quality control techniques will be necessary to assure maintenance of skills?

5. Can automation be used to successfully increase the rate of skill acquisition in complex tasks by automating some of the subtasks? Will the operator who is learning in this mode be better at detecting anomalies in other parts of the process? Will the necessity of learning to operate the automatic equipment (perhaps a complex process itself) negate any of the gains of automating subtasks?

## 4.3 Monitoring of complex systems

The experimental and theoretical research on vigilance deals primarily with human perceptual processes; for example, detecting the presence of a light. Most systems, however, require much more cognitive processing to perform the monitoring task. For example, a typical pilot assessment of his fuel situation might proceed as follows: the aircraft is traveling at 200 miles/hr and is 100 miles or 100 ÷ 200 = 0.5 hr from the destination; it is burning fuel at the rate of 100 gal/hr and therefore requires 0.5 × 100 or 50 gal to reach the destination; there are 40 gal of fuel remaining, so the destination cannot be reached.

Beyond this very simple but highly realistic case, there are many situations that require cognitive functions; for example, logical, mathematical, and memory operations utilizing multiple sources of information. The major issues in this complex monitoring are essentially those that confronted researchers in the vigilance area, but they have to be examined for the more complex situations.

1. Does complex monitoring performance degrade with time on watch? If so, is this decrement perceptual, cognitive, or criterial?

2. What are the means for maintaining operator alertness for rare signals? Will artificial signals and alerts improve or degrade monitoring effectiveness? Will additional workload, in addition to complex monitoring, improve or degrade performance?

3. What makes an automatic system more "interpretable," that is, easier to detect and diagnose malfunctions?

## 4.4 Alerting and warning systems

Human behavior with alerting and warning systems is one of the most fascinating topics in man-machine interaction. It is here that one sees both unpredictable and predictable responses. For example, it has long been recognized that people will ignore an alarm if experience has shown that the alarm may be false (the boy who cried wolf); we see the same behavior with some cockpit alarms today. Important research questions for alerting and warning systems include:

1. What are the characteristics of an ideal (but attainable) alerting and warning system?
2. What attributes make a false alarm rate unacceptably high?
3. Why do alarms apparently go unheeded?
4. Under what conditions do operators rely on alerting and warning systems as primary devices rather than as backup devices? Is this operationally sound?
5. Under what conditions will operators check the validity of an alarm?
6. Should the responsible operator be given a preview alert and opportunity for corrective action before the alarm is given to others?
7. A consensus seems to be building to develop alerting and warning systems that are "smart"; among other things, they would prevent "obvious" false alarms and prioritize alarms. The logic for these systems will likely be exceedingly complicated. Will that logic be too complex for operators to perform validity checks, and thus lead to over-reliance on the system? Will the priorities <u>always</u> be appropriate? If not, will the operators recognize this?

## 4.5 Psychosocial aspects of automation

The psychosocial aspects of automation may prove to be the most important of all, because they influence the basic attitudes of the operator toward his task and, we would presume, his motivation, adaptability, and responsiveness. The significance of these questions lies not in the spectre of massive unemployment due to assembly line automation, but in the effects of automation on the changing role of a few highly skilled operators.

1. Will automation influence job satisfaction, prestige, and self-concept (especially in aviation)?

2. If there are negative psychosocial consequences of automation, what precautions and/or remedies will be effective without changing the use of automation?

3. What does increased automation imply for operator selection? Are there clearly defined aptitudes or personality attributes that imply better monitoring (or manual) effectiveness?

4. How should training programs be altered to deal with possible psychosocial effects? Would a simulator help support morale? If so, what type of simulation?

## 5. Design decisions

The words "cockpit automation" are usually interpreted to mean autopilots, flight directors, and other equipment associated with the control of the aircraft flightpath. Interpreting automation to mean the accomplishment of a task by a machine instead of a human leads to the realization that all cockpit alerting and warning systems are forms of automation also, since they perform monitoring tasks. Automation of control and automation of monitoring are quite independent of one another; it is possible to have various levels of automation in one dimension (see figure 1) independent of the other. Automation of control tasks implies that the operator is monitoring the computer, whereas automation of the monitoring tasks implies that the computer is monitoring the operator. Both of these dimensions will be explored in the context of design decisions after a discussion of the overall goals of the system.

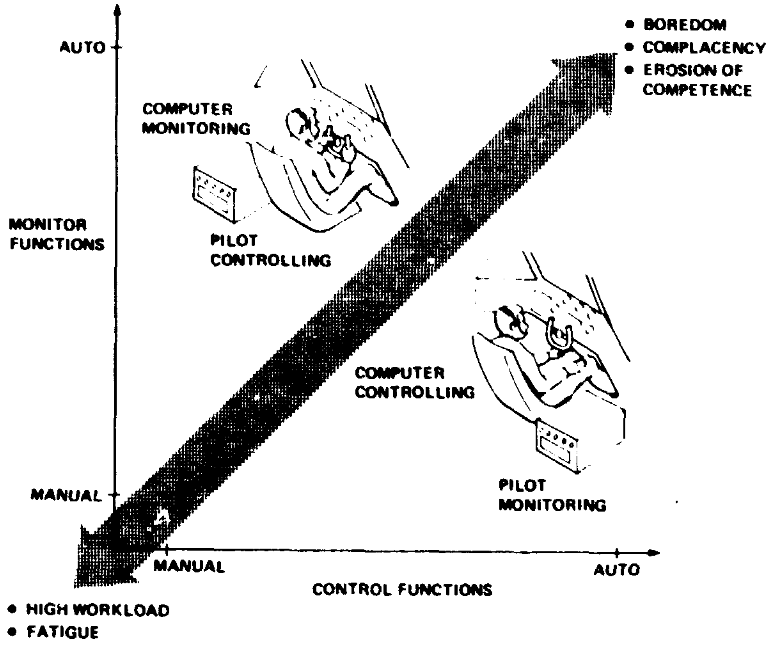

Figure 1.- Two dimensions of automation: control and monitoring.

## 5.1 System goals

Let us begin by asking what the user expects of the system. Some of the goals of the system are:

1. To provide a flight (from pushback to docking) with infinitesimal accident probability.

2. To provide passengers with the smoothest possible flight (by weather avoidance, selection of the least turbulent altitudes, gradual turns and pitch changes, and gradual altitude changes).

3. To conduct the flight as economically as possible, minimizing flight time, ground delays, fuel consumption, and wear on the equipment.

4. To minimize the effect of any flight on the ability of other aircraft to achieve the same goals (e.g., by cooperation with ATC in rapidly departing altitudes when cleared, freeing them up for other aircraft).

5. To provide a pleasant, safe, and healthful working environment for the crew.

Now that the goals of the system have been annunciated, several things should be clear. First, the goals are exactly the same whether the systems are automated or manual. Whether flight-deck automation can help achieve these goals, and whether it is feasible and economical to do so, remains to be seen. (For a totally optimistic view, see Boulanger and Dai (1975).) Second, for the most part, these goals are not in conflict. There are exceptions; for example, it is clear that (2) above may be in conflict with (3). The resolution of this conflict lies in evaluating the utilities to the airline, no easy job in itself. If the utilities can be made explicit, then the resolution could be automated. For example, one could envision an onboard flight management system that would take into account the utilities of extra cost of weather avoidance versus the discomfort to passengers. The system would then, within certain constraints, navigate over a course and altitude of maximum utility. If the reader prefers, let him substitute "recommend to the crew" for "navigate over." Likewise, (2) and (4) may at times be in conflict — a very rapid descent would be helpful to ATC in clearing altitude for other traffic, but may adversely affect both passenger comfort and fuel consumption. Again, while these are not problems of automation *per se*, automation in the cockpit (and elsewhere) may aid in their resolution, forcing the designer to face the question of utilities.

## 5.2 Design philosophies — control

So far we have specified system goals and constructed, at least, a justification for considering automation as a means to reaching those goals, along with some cautions. We must now consider design philosophies centered on the man-in-the-loop question. In simple terms, the designer must ask to what extent the human should be included in the control loop at all (Sinaiko 1972).

This is considerably more than restating the time-honored cliches about "Man can do these things better than machines, but machines can do these better," which were so in fashion in the early days of ergonomics. Since the authors have already ruled out unmanned airline flight (by assumption), the question must now be restated, "Under what conditions should man be part of the control loop, and what price is paid, in terms of attaining system goals, for including or excluding him?" One paridigm is diagrammed in a paper by Johannsen (1976). His scheme envisions nested control loops, with inanimate devices controlling the inner (high bandwidth) loops, and an outward progression toward lower bandwidth, where the human is inserted as controller-monitor.

Using this framework, let us imagine the control of a typical flight. An example of the highest bandwidth control task is yaw damping, to prevent the aircraft from entering an oscillatory "Dutch roll" mode. This activity is usually beyond the frequency domain of the human and is thus assigned to an automatic control device, a yaw damper, one that is built in and unregulated by the flightcrew.

Progressing outward, one encounters the moment-to-moment directional control of the aircraft — which can be either hand-flown or handled by autopilot. At cruise, the least critical portion of the flight, designers and pilots are only too happy to turn control over to the autopilot, allowing the flightcrew to occupy themselves with other things. In the more critical segments of the flight, use or nonuse of the autopilot is largely a matter of personal style of the flightcrew.

Control of the autopilot during level flight at an assigned altitude would be a happy state of affairs were it not for the fact that autopilots have a disconcerting way of failing "gracefully," so gracefully that a decoupling may not be noticed by the crew until the system is badly out of limits, if then. Two interesting examples can be cited. First, a PAA B-707, which was cruising at 36,000 ft above the Atlantic, experienced a graceful autopilot disengage. The aircraft, which went into a steep descending spiral before the crew took action, lost 30,000 ft before recovery (Wiener 1962). A second case, the crash of an Eastern Airlines L-1011 in the Everglades, was discussed in Section 3.6.

Continuing outward, the next loop might be navigation (lateral and vertical), where from time to time heading changes would affect directional control, and pitch and power changes would affect the vertical position. In more advanced autopilot/flight-management systems, much of this (at least the lateral portion) can be preprogrammed. Alternatively, the man in the loop could use his autopilot (or manual controls) to make the necessary changes. A more demanding control task would be final approach navigation — merely a special case of lateral and vertical navigation, but one that combines relatively high bandwidth with low error tolerance. At this point, the man-in-the-loop design philosophies become controversial.

An excellent example of the intrusion of basic design philosophy into equipment concepts is the controversy that continues to swirl around the head-up display (HUD). At issue is the HUD's utility for aiding the pilot making a low-ceiling, low-visibility approach, below those permitted with conventional head-down displays, even when aided by autothrottles and flight directors. The two philosophies are exemplified in a paper by Naish and Von Wieser (1969), which was strongly supportive of retaining the man in the loop by means of providing a HUD, and by St. John (1963) who wished to remove the man entirely from controlling a final approach by using more sophisticated autoland equipment. The argument in favor of the HUD is that it allows one crewmember to remain "head up," so that when the runway becomes visible, the transition from instruments to outside reference is facilitated. The "head up" pilot would then fly so as to visually superimpose the HUD runway symbology on the actual runway.

Others feel that the intervention by the pilots could introduce nothing but error to an autoland approach — they prefer to have the autopilot-autothrottle capacity used all the way to the runway, with the pilots keeping hands off and only monitoring (as in the extreme lower right of figure 1). The middle ground would be an autoland approach monitored by a headup display. This procedure is gaining favor and is currently operational on some European carriers.

The reader should note that at least one piece of cockpit instrumentation, the flight director, stands in contrast to the nested-loop configuration we have been describing. A flight director takes essentially outer-loop decisions about navigation and computes steering commands for the pilot (or autopilot), relieving him of complex information processing requirements.

Finally, one might conceive of outermost loops where control decisions are made only occasionally — initial flight planning or enroute changes (such as weather avoidance, diversion to an alternate destination, or handling of critical in-flight events). Many such decisions could be automated, but presently are not. We predict that the actual decisions would always remain in the domain of the pilot for a variety of reasons: complexity, the cost of developing and maintaining software, legal liability, and social pressures, just to name a few. Even in the most fully automatic mode, the equipment would process information and present alternatives to the pilot, who would weigh the results and make the command decision. The intriguing question is the many forms the crew-computer interaction might take. For example, does the automatic equipment merely compute alternatives, or should it suggest a "best" choice to the pilot? What role could automation play in multi-attribute decisions? Let us take, as an example, the choice of an alternate airport if it becomes necessary to divert. Pertinent attributes of the candidate airports include the present weather, the forecast weather, type of instrument approach available, passenger facilities, maintenance facilities, runway length and conditions, fuel cost at the destination, surrounding terrain, and many more. Automation or not, the captain must ultimately process multidimensional information and make a decision, often between conflicting objective functions. Our question, once again, is how may automation assist the pilot in making his decision?

## 5.3 Design philosophies — monitoring

Until recently, there has been little consensus on a design philosophy for automatic alerting and warning systems other than to install a warning device to alert the pilot to a condition that existed in some recent and serious accident. This, and the desire to cover all situations with alerts or warnings, has led to a proliferation of independent warning and alerting devices which many feel has reached the point of saturating pilot information processing capabilities (Randle et al. 1980). For example, there are 188 warnings and caution alerts on the B-707, 455 on the B-747, 172 on the DC-8, and 418 on the DC-10. The aviation industry seems to feel that the time has come for the development of integrated alerting and warning systems (Cooper 1977).

It has been stated that man is a poor monitor, yet for detecting some situations (e.g., incapacitation or aberrant behavior of other crewmembers) man is clearly superior to any automatic monitor. If he does have monitoring difficulty in large transport aircraft, it would appear to arise from the requirement that he monitor a large number of systems and perform other duties at the same time. In spite of many laboratory studies showing the parallel processing capabilities of the human, pilots generally perform many of their tasks as single-channel processors, especially when a task is somewhat out of the ordinary. It is not uncommon, for example, to see pilots concentrate on lateral navigation during a difficult intercept maneuver to the exclusion of airspeed control.

In summary, the primary necessity for automation of the monitoring functions is the single-channel behavior of the human and the increased number of devices or conditions to be monitored. Increasing the number of individual alerts and warnings is not the complete answer to the problem, however, since one anomaly may lead to a large number of alerts, many of which are superfluous or, worse, misleading; thus, the industry emphasis on integrated alerting and warning systems (Randle et al. 1980).

## 5.4 Strengths and weaknesses

At the risk of stumbling into the trap of "Man does this better, machines do this better," the authors close this section by summarizing and generalizing about some of the positive and negative features of cockpit automation. The generalizations contained in table 1 probably apply to the flight deck, and may apply equally well to manufacturing, ATC, medicine,

TABLE 1.- GENERALIZATIONS ABOUT ADVANTAGES AND DISADVANTAGES OF AUTOMATING MAN-MACHINE SYSTEMS.

| Advantages | Disadvantages | Questionable | Unknown |
|---|---|---|---|
| Increased capacity and productivity | Seen as dehumanizing; lower job satisfaction; consumer resistance | Overall workload reduced or increased? | Capital acquisition costs |
| Reduction of manual workload and fatigue | Low alertness of human operators | Total operational cost increased or decreased? | Use of common hardware (e.g., standard mainframe computers) |
| Relief from routine operations | Systems are fault intolerant — may lead to larger errors | Training requirements increased or decreased? | Maintenance costs |
| Relief from small errors | Silent failures | Reduction in crew size? | Extent of redundancy necessary and desirable |
| More precise handling of routine operations | Lower proficiency of operators in case of need for manual takeover | | Long-range safety implications |
| Economical utilization of machines (e.g., energy management) | Over-reliance; complacency; willingness to uncritically accept results | | Long-range effect on operators and other personnel (including physical and mental health, job satisfaction, self-esteem, attractiveness of job to others entering field) |
| Damping of individual differences (narrower tolerances) | False alarms | | Long-range implications for collective bargaining |
| | Automation-induced failures | | Implications for civil liability (e.g., software error resulting in an accident) |
| | Increase in mental workload | | |

telecommunications, power generation, and many nonaviation examples of highly automated systems. Our focus, of course, is on the flight deck.

## 6. Automation guidelines

In this section we propose some guidelines for designing and using (or not using) automated systems. These guidelines should be considered in addition to the usual human factors engineering requirements. The guidelines are not to be considered as specifications, since most lack the detail needed for that purpose, and conditions exist where they may not be appropriate. Moreover, there are many conflicting concepts within these guidelines. Because we have tried to make them comprehensive, some may appear to the reader to be quite obvious.

### 6.1 Control tasks

1. System operation should be easily interpretable or understandable by the operator to facilitate the detection of improper operation and to facilitate the diagnosis of malfunctions.
2. Design the automatic system to perform the task the way the user wants it done (consistent with other constraints such as safety); this may require user control of certain parameters, such as system gains (see guideline 7). Many users of automated systems find that the systems do not perform the function in the manner desired by the operator. For example, autopilots, especially older designs, have too much "wing waggle" for passenger comfort when tracking ground-based navigation stations. Thus, many airline pilots do not use this feature, even when traveling coast to coast on nonstop flights.
3. Design the automation to prevent peak levels of task demand from becoming excessive (this may vary from operator to operator). System monitoring is not only a legitimate, but a necessary activity of the human operator; however, it generally is second in priority to other, event-driven tasks. Keeping task demand at reasonable levels will ensure available time for monitoring.
4. For most complex systems, it is very difficult for the computer to sense when the task demands on the operator are too high. Thus, the operator must be trained and motivated to use automation as an additional resource (i.e., as a helper).
5. Operators should be trained, motivated, and evaluated to monitor effectively.

15. Devise training techniques and possibly training hardware (including part- and whole-task simulators) to insure that flightcrews are exposed to all forms of alerts and to many of the possible combinations of alerts, and that they understand how to deal with them.

## 7. Conclusions

There are many potential safety and economic benefits to be realized by automating cockpit functions, but the rapid pace of automation is outstripping one's ability to comprehend all the implications for crew performance. It is unrealistic to call for a halt to cockpit automation until the manifestations are completely understood. We do, however, call for those designing, analyzing, and installing automatic systems in the cockpit to do so carefully; to recognize the behavioral effects of automation; to avail themselves of present and future guidelines; and to be watchful for symptoms that might appear in training and operational settings. The ergonomic nature of these problems suggests that other sectors of aviation and, indeed, other industries, are or will be facing the same problems.

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