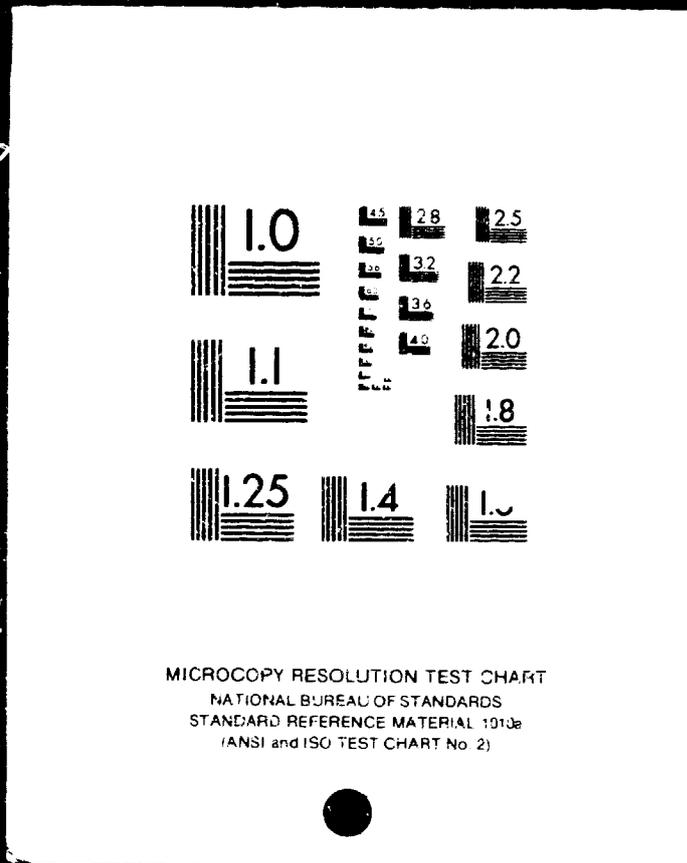


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Human-Centered Aircraft Automation: A Concept and Guidelines

Charles E. Billings

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Human-Centered Aircraft Automation: A Concept and Guidelines

Charles E. Billings, Ames Research Center, Moffett Field, California

August 1991

NASA

National Aeronautics and
Space Administration

Ames Research Center

Moffett Field, California 94035-1000

DEDICATION

This document is dedicated to the memory of Dr. Alan B. Chambers, former Chief of the Man-Vehicle Systems Research Division and late Director of Space Research at Ames Research Center, whose encouragement and support of human factors research were largely responsible for the creation of a strong and healthy aeronautical human factors research program at the Center.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

Note: Where appropriate, acronyms and abbreviations used herein conform to FAA-approved acronyms as used in the Airman's Information Manual and other regulatory and advisory material. Acronyms and abbreviations used for cockpit devices by specific manufacturers or in specific aircraft are indicated.

AC	Abbreviation for "aircraft".
ACARS	ARINC (qv) Communications and Address Reporting System.
AERA	Automated En Route Air Traffic Control, the FAA's advanced ATC system concept.
ARINC	Aeronautical Radio, Incorporated, provides data forwarding services for air carriers.
ASC	Aircraft System Controller (McDonnell-Douglas MD-11).
ASDE	Airport Surface Detection Equipment (radar).
ASRS	NASA Aviation Safety Reporting System, a voluntary, confidential incident reporting system operated by NASA for FAA.
ATA	Air Transport Association of America, the U.S. air carrier industry organization.
ATC	Air Traffic Control system.
CADC	Central air data computer.
CDU	Control and display unit: the flight management system human-system interface.
CFIT	Controlled flight into terrain.
CRT	Cathode ray tube.
CVR	Cockpit voice recorder.
DME	Distance measuring equipment, an element in the common navigation system.
Doppler	Aircraft-based navigation system making use of Doppler radar to sense rate of change of position.
E-MACS	Engine Monitoring and Control System (ref. 61).
EAD	Engine and Alert Display (McDonnell-Douglas MD-11).
ECAM	Electronic Centralized Aircraft Monitoring System (Airbus Industrie A310, A320).
EEC	Electronic Engine Controller (Boeing 757/767).
EGT	Exhaust gas temperature.
EICAS	Engine indication and crew alerting system (Boeing 757/767, 747-400, 777).
ESPRIT	Literally, "spirit": European Strategic Program for Research and Development in Information Technology.
F-PLN	Abbreviation for "flight plan".
FAA	Federal Aviation Administration.
FADEC	Full authority digital engine controller.
FMC	Flight management computer.
FMS	Flight management system.
GPS	Global positioning system, a satellite-based navigation system.
GPWS	Ground proximity warning system.
GS	Glide slope, the vertical path generated by a surface transmitter for instrument approaches; an element of the instrument landing system.
HSI	Horizontal situation indicator, either electromechanical or glass cockpit display.
ILS	Instrument landing system, consisting of localizer and glide slope transmitters on the ground. Also used to describe an approach conducted using ILS guidance.
INTC	Abbreviation for "intersection", a waypoint in a navigation plan.

INS Inertial navigation system, an airborne system of gyroscopes and accelerometers that keeps track of aircraft movement in three spatial axes.

IVSI Instantaneous vertical speed indicator, an electromechanical instrument using air data quickened by acceleration data; also the display of such information on a primary flight display in a glass cockpit aircraft.

KLM Royal Dutch Airlines.

LAF Load Alleviation Function (Airbus Industrie A320), automation that acts on wing control surfaces to smooth the effect of gusts in flight.

LCD Liquid crystal display.

LOC Localizer, a surface transmitter that delineates a path to an instrument runway; a component of the ILS. Also, the path so delineated.

LORAN Long-range navigation system, ground-based low-frequency radio aids providing triangulation-based position derivation for aircraft and surface vehicles.

MCP Mode control panel: the tactical control panel for the autoflight system; almost always located centrally at the top of the aircraft instrument panel.

MITRE MITRE Corporation, an engineering firm that conducts systems analyses and provides engineering technical support and guidance to the FAA, Department of Defense and others.

MLS Microwave landing system, a high-precision landing aid which provides the capability for curved as well as straight-in approaches to a runway, and conveys certain other advantages. The system is in advanced development and verification testing by FAA.

NASA National Aeronautics and Space Administration.

NTSB National Transportation Safety Board.

PERF Abbreviation for "performance".

PFD Primary flight display, usually electronic.

QRH Quick reference handbook, a booklet containing aircraft operating procedures, especially abnormal and emergency procedures.

RMI Radio magnetic indicator, an electromechanical instrument showing magnetic heading and bearing to VOR or low frequency nondirectional radio beacons.

RNAV Area navigation system, a generic acronym for any device which is capable of aircraft guidance between pilot-defined waypoints.

SAS Scandinavian Airlines System.

SID Standard instrument departure procedure.

STAR Standard arrival route, like SID, an FAA-approved arrival route and procedure.

TCAS Traffic alert and collision avoidance system.

UHF Ultra-high frequency, a portion of the electromagnetic spectrum used for aeronautical communications and navigation.

VHF Very high frequency, a portion of the electromagnetic spectrum used for aeronautical communications and navigation.

VOR Very high frequency Omnidirectional Range, a surface radio navigation beacon transmitter which forms the core of the common short-range navigation system for aircraft.

INTRODUCTION

The purposes of this document are to examine aircraft automation and its effects on the behavior of flight crews, and to propose guidelines for the design and use of automation in transport aircraft, in order to stimulate increased dialogue between designers of aircraft, automation designers, and aircraft operators and pilots. The goal is to explore the means by which automation can be made a more effective tool or resource for pilots without compromising, and hopefully with an increase in, aviation system safety. Human error is the dominant cause of aircraft accidents. Most of these accidents are avoidable. The most important purpose automation can serve is to make the aviation system more error resistant and more error tolerant.

Automation at some level has been applied to aircraft since before World War I (ref. 1). It has been an invaluable aid to pilots flying special missions from 1930 onward. On July 24, 1933, the *New York Times*, reporting on Wiley Post's just-completed solo flight around the world, said, "By winning a victory with the use of gyrostats, a variable-pitch propeller and a radiocompass, Post definitely ushers in a new stage of long-distance aviation... Commercial flying in the future will be automatic" (ref. 2). Automation-assisted flight has been routine in military and civil air transport since shortly after World War II.

Crew-centered automation principles incorporating automated devices that assist in flight path and aircraft management have made it feasible to certify and operate complex transport aircraft safely with a crew of two rather than three persons, just as the development of automated area navigation systems (Doppler, INS, LORAN) had replaced the navigator some years before and improvements in radio communications had supplanted the radio operator still earlier. The report of the President's Task Force on Aircraft Crew Complement stated, "We believe that from an aircraft systems standpoint, the level of safety achieved by the B-757, B-767, and A-310 might be even higher than that achieved in present-generation aircraft as a result of the increased redundancy, reliability, and improved information that are to be provided the flight crews through more extensive use of digital avionics and cathode ray tube (CRT) displays" (ref. 3).

More recently, aircraft have been introduced with fly-by-wire control systems incorporating envelope protection that prevents pilots from flying outside a predetermined flight envelope, advanced flight management systems that automate navigation and flight path management, and automated subsystems management computers that relieve the crew of essentially all routine subsystem management tasks. Indeed, the McDonnell-Douglas MD-11, now entering service, reconfigures aircraft subsystems automatically after certain hardware failures, reducing flight crew involvement in subsystems management still further (ref. 4). The MD-11 also attempts to infer the intentions of the pilots in certain flight regimes and adjusts aircraft and engine parameters automatically to conform with recommended operating procedures for those phases of flight. The Boeing 777, now in design, and other new aircraft may incorporate electronic libraries which will automate much of the information management now performed manually (ref. 5).

Two-person, highly automated aircraft have been in service for ten years, during which time accident rates in United States air transport have remained level except for secular variation, or have declined. The President's Task Force in 1981 commented that "the increased use of automation on the DC-9-80 has led to a change in the number, but not the nature, of the tasks that the pilot performs compared to the DC-9-50. The role of the pilot is unchanged" (ref. 3). There is certainly no evidence that transport flying has become less safe since the introduction of highly automated aircraft, and there is some evidence that safety has improved. What, then, is the problem that motivates this document? And why, in the face of this safety record, has the Air Transport Association (ATA) of America cited aircraft automation as the first element in its "National Plan to Enhance Aviation Safety through Human Factors Improvements" (ref. 6)?

Although accident rates have been stable or have declined during the past two decades, evaluation of individual accident and incident reports reveals two contrary trends. First, there has been a sharp decline in accidents caused by controlled flight into terrain (CFIT) since the introduction of ground proximity warning systems (GPWS) into transport aircraft in 1975. There is some evidence that CFIT accidents have been replaced by incidents involving "controlled flight toward terrain" (ref. 7), but it appears that the Congressionally-mandated introduction of automated terrain proximity sensors and alerting systems has been largely successful in preventing most accidents of this type in aircraft of the nations that require GPWS.

The success of GPWS has been one of several factors that has motivated the U.S. Congress to require the installation, during the next two years, of wind shear alerting devices and collision avoidance systems in transport aircraft (refs. 8 and 9). Like GPWS, these devices can detect conditions that may not be obvious to human pilots. Also like GPWS, these devices are advisory in nature; they alert pilots to the presence of a problem, but do not perform avoidance maneuvers at this time.

There is a contrary trend, however. Several aircraft accidents and a larger number of incidents have been associated with, and in some cases appear to have been caused by, aircraft automation or, more accurately, by the interaction between the human operators and the automation in the aircraft. In some cases, among them a Northwest MD-82 at Detroit (ref. 10) and a Delta B727 at Dallas (ref. 11), automated configuration warning devices failed or were rendered inoperative. In other cases, an Aeromexico DC-10 on departure from Frankfurt (ref. 12) and an Indian Airlines A320 landing at Bangalore (ref. 13), automation has operated in accordance with its design, but in a mode incompatible with safe flight under particular circumstances. In still other cases, automated devices have not warned, or flight crews have not detected, that the devices were operating at their limits, as in the China Airlines 747 accident offshore from San Francisco (ref. 14), or were operating unreliably, as in the SAS DC-10 landing accident at New York (ref. 15).

Data from incident reports also suggest that automated information systems, originally installed as backup devices for pilots, have become *de facto* primary alerting devices after periods of dependable service. These devices were originally prescribed as a "second line of defense" to warn pilots when they had missed a procedure or checklist item. Altitude alerting devices and configuration warning devices are prime examples (ref. 16). In the Northwest and Delta accidents mentioned above, the flight crews should have, but apparently did not, check the configuration of their aircraft before takeoff as their procedures required. The automated warning systems failed to warn them that they had not performed these checks. In these cases, the presence of (and reliance upon) usually reliable automation may have affected the mind-sets and behaviors of the pilots being served by it.

Accidents and incidents associated with or caused, in whole or in part, by automation constitute a new class of potentially preventable mishaps in transport aviation. As such, they represent a new threat to safety, the paramount concern of the aviation industry. It is estimated that passenger enplanements will increase 75% by the turn of the century (ref. 17). It is not enough to maintain accident rates at *any* non-zero level in the face of our current surge in air transport activity; the *number* of highly publicized, enormously expensive accidents will rise unless rates can be reduced further. It is for this reason that the ATA's National Plan stated that "During the 1970's and early 1980's...the concept of automating as much as possible was considered appropriate. The expected benefits were a reduction in pilot workload and increased safety...Although many of these benefits have been realized, serious questions have arisen and incidents/accidents have occurred which question the underlying assumption that the maximum available automation is ALWAYS appropriate or that we understand how to design automated systems so that they are fully compatible with the capabilities and limitations of the humans in the system."

The ATA report discussed specific issues, and went on to say, "The fundamental concern is the lack of a scientifically based philosophy of automation which describes the circumstances under

which tasks are appropriately allocated to the machine and/or the pilot." The report then defined an approach to this domain, which in large part has been the motivation for this document.

To summarize: if there is a perceived problem, there is probably a real problem. Whether it is precisely the problem that is perceived is often susceptible to analysis but may be of little importance in the long run. The aviation community clearly perceives that automation conveys important benefits, but it also perceives in automation a potential threat to air safety. Most automation-related mishaps may be preventable, just as most accidents involving human factors are preventable. We must therefore try by every means at our command to prevent them.

If automation is required, there must be an internally-consistent philosophy to govern its design and application. Accident, incident (ref. 18), and field study (ref. 19) data indicate that the concerns of the aviation community (ref. 6) are well-founded—that automation conveys important benefits but that it can also pose new problems. We suggest a concept for a philosophy of human-centered automation and will attempt herein to define its elements in terms of what is known about human behavior and air transport operations.

This paper does not purport to be a designer's handbook. We have not attempted to cover in any detail the myriad details of human factors engineering that determine how a cockpit should be designed once a designer has determined what that cockpit should contain. Rather, we attempt to suggest questions that should be answered before beginning the design of the automation suite for an advanced-technology aircraft. The report is aimed primarily at three groups: cockpit designers, purchasers of automated aircraft and the pilots who must fly them in line operations. They are thought of, respectively, as the creators, purchasers and end users of advanced aircraft automation. To be effective, automation must meet the legitimate needs and constraints of each of these groups.

It is hoped that this document will provoke discussion within our community about what automation should be like in future aircraft: what roles automation should play in future aircraft, how much authority it should have, how it will interact with the human operator, and what, if any, roles should be reserved for the human. We draw extensively on the automation of today, without in any sense intending to be critical of the enormously capable aircraft now being flown safely in our aviation system. But the perfect design has never existed and probably never will; too many tradeoffs must be made in the course of the design process, and automation design involves complex and imprecisely understood interactions between human cognition and sophisticated information processing machines.

In the first section of this paper we define some terms, look briefly at the development of pilot aiding devices, then present our concept of human-centered automation and of the role of the human in highly automated systems. In the second section we examine in more detail various kinds of aircraft automation that have been used to date in an effort to discern what has worked well, what has worked less well, and why. We also examine trends in automation that may be applied in aircraft in the near-term future in order to identify issues that may arise from its implementation. In the third section we look at the environment in which new automation will be introduced and used, and the people who will use it, to determine factors that may interact, favorably or unfavorably, with that automation. In the fourth section we review guidelines that have been proposed in the past and suggest desirable attributes for present and future automation. The final section is devoted to a more detailed discussion of suggested guidelines for the application of human-centered aircraft automation. An appendix provides brief descriptions of aircraft mishaps cited in the text.

The style of presentation is essentially didactic, though we attempt to explain the basis for our conclusions. Automation is an art as much as a science, just as architecture is an art as well as an engineering discipline. It cannot be approached from the standpoint of pure reason, nor can we make the mistake of believing that there is but one best way to design, construct or even operate automated devices. Many elements of this document are therefore arguable, but we suggest that

the very process of arguing about them will in itself bring us closer to our goal of effective, safe aircraft automation.

What follows is the product of 35 years of observing and working with pilots, operators, air traffic controllers and aircraft manufacturers to try to build a safer national aviation system. It is hoped that this report will be perceived as useful by the community whose guidance and forbearance over a long period of time made its creation possible.

Charles E. Billings
August, 1991

I: CONCEPTS

Assumptions and Definitions

The ATA Human Factors Task Force states in its 1989 report, "This plan assumes that humans will continue to manage and direct the National Aviation System through the year 2010. The pilot and the controller will both be integral parts of the air and ground system. Automation should therefore be designed to assist and augment the capabilities of the human managers" (emphasis added).

Automation, as used herein, refers to "a system or method in which many of the processes of production are automatically performed or controlled by self-operating machines, electronic devices, etc." Here, our concern is with aircraft automation specifically, though we will discuss other elements of the aviation system insofar as they impact the aircraft and pilots. We do so because the aircraft is the device managed or controlled in the aviation system, regardless of how that control is exercised or where the locus of control may be. Even remotely-controlled aircraft must still be controlled or managed by a pilot; the automation through which the task is performed does not operate entirely autonomously, and the automation, we would argue, must still be human-centered if the system is to operate effectively. We do not consider air traffic control except insofar as it influences the management and control of aircraft.

By "human-centered automation," we mean automation designed to work cooperatively with human operators in the pursuit of stated objectives. We consider automation to be a tool or resource—a device, system or method by which the human can accomplish some task that might otherwise be difficult or impossible, or which the human can direct to carry out more or less independently a task that would otherwise require increased human attention or effort. The word "tool" does not foreclose the possibility that the tool may have some degree of "intelligence"—some capacity to learn and then to proceed independently to accomplish a task. Automation is simply one of many resources available to the human operator, who retains the responsibility for management and direction of the automation and the overall system.

The Piloting Domain

We conceptualize piloting as the use by a human operator of a vehicle (an aircraft) to accomplish a mission (to move passengers and cargo between two points) (fig. 1). Rouse (ref. 20) states that "design objectives should be to support humans to achieve the operational objectives for which they are responsible. From this perspective, the purpose of a pilot is not to fly the airplane that takes people from A to B—instead, the purpose of the airplane is to support the pilot who is responsible for taking people from A to B."

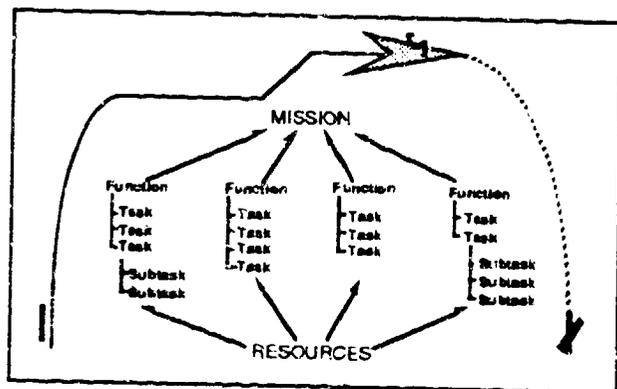


Figure 1: Elements of the piloting domain

The mission requires more-or-less simultaneous accomplishment of five categories of functions: inner-loop control of airplane attitude and state, control of the flight path in three dimensions, management of airplane position, management of its systems, and maintenance of communications with the entities responsible for its movements. Each of these functions may be decomposed into a number of tasks, which may sometimes involve several subtasks. Tasks (many of which may be carried out either by humans or by machines) are performed utilizing a combination of resources.

The resources available to the pilot include his or her own perceptual, cognitive and psychomotor skills, the knowledge and skills of other flight and cabin crewmembers, the knowledge and information possessed by other persons with whom the pilot may be able to communicate, and a variety of information sources and control devices, including the automated devices, within the aircraft. These resources are controlled and managed by a pilot in command, who is ultimately responsible for safe mission accomplishment.

Control and management of an aircraft may be viewed as a series of levels, which are categorized by the degree of direct or immediate involvement of the pilot (fig 2).

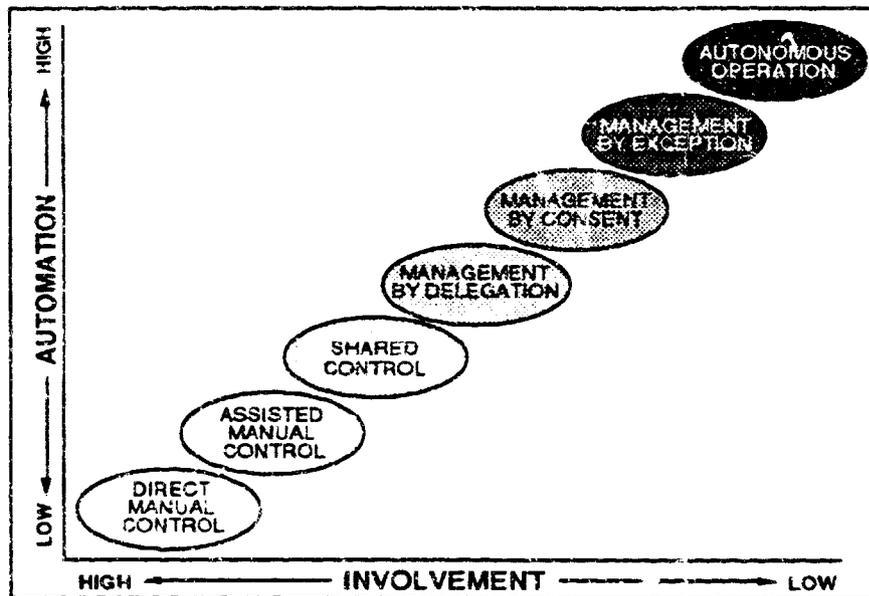


Figure 2: Pilot control and management continuum

Development of Pilot Aiding Devices

Not all of the functions required for mission accomplishment in today's complex aircraft are within the capabilities of the unaided human operator, who lacks the sensory capacity to detect much of the information required for flight and who is unable to make certain decisions or take actions based on them within the time available for accomplishment of certain critical tasks. In the early days of aviation, the pilot set forth unaided, with only human perceptual capabilities to provide necessary information. It was soon discovered that these were insufficient, and aircraft sensors and instruments were developed to augment the limited human capabilities.

Even before the first powered flight in 1903, aircraft designers had recognized the instability of their machines and had begun to work toward providing pilots with assistance in controlling the vehicles. The Wrights worked toward development of a stability augmentation device in 1907 (fig. 3); they were preceded by Sir Hiram Maxim, who patented the first such device in 1891 (ref. 21). Orville Wright was awarded the Collier Trophy in 1913 for a demonstration of hands-off flight using an automatic stabilizer. By the 1930s, autopilots were considered essential for long-distance flying. The introduction of retractable landing gear was accompanied by a requirement for configuration warning systems. The introduction of four-engine aircraft led to the development of automatic propeller synchronizing devices. Some World War II aircraft were difficult to control if an engine failed on takeoff; automatic propeller feathering devices were consequently introduced for these aircraft. The development of improved electronics led to the capability for automatic navigation. The introduction of digital computers enabled the design of on-board flight and performance management systems and, later, of tailored flight control systems.

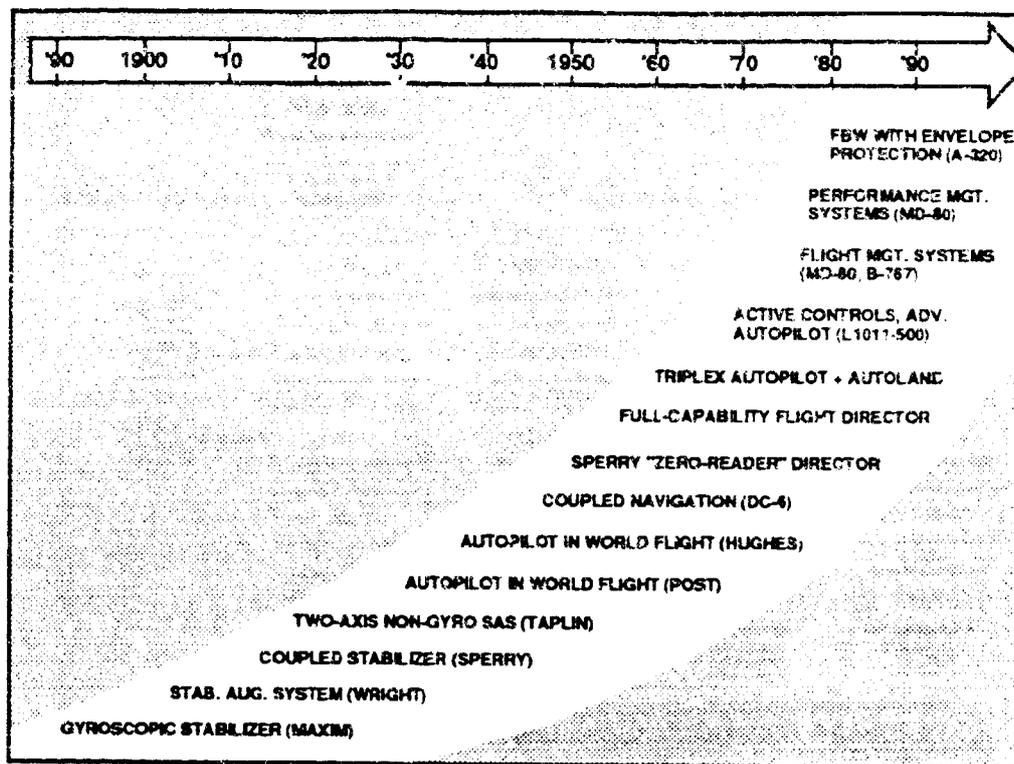


Figure 3: A brief chronolog of aircraft automation

Since shortly after World War II, nearly all transport aircraft have made extensive use of automated devices to assist and augment the capabilities of the flight crew. The advent of turbojet transports during the 1950s introduced new requirements for automation. These aircraft were considerably faster than their predecessors, and were less aerodynamically stable. The requirement for very precise control, particularly during approach to landing, led to the development of new classes of pilot aids including flight directors, expanded and quickened displays, and stability augmentation devices.

The demands on the pilot-vehicle system became progressively greater, both in the area of precision navigation and in requirements for more reliable all-weather operation. Precision navigation over land was enabled by the introduction of very high frequency (VHF) omnidirectional range systems (VOR) and, later, distance measuring equipment (DME). Long-range navigation over water was immeasurably aided by the development of area navigation systems—first Doppler, later inertial navigation devices that freed aircraft from dependence on ground radio aids. Precision approach aids, primarily instrument landing systems (ILS) and improved approach and touchdown zone lighting were introduced. Static-free VHF communications equipment became standard for short-range radio communications.

The development of compact solid-state electronics made it possible to accomplish much more computation within the aircraft. Contemporary aircraft may contain well over 100 computers and microprocessors, which assist in the control of aircraft state and energies, flight path management and aircraft systems management. They may also assist cabin crew in certain of their duties. Flight and performance management computers perform most tactical navigation chores; sophisticated digital autopilots, interfaced with the flight management systems, control aircraft attitude and thrust from takeoff to landing roll-out. Electronic flight displays are managed by computers, as are the detection and monitoring of aircraft state and system parameters. In the newest vehicles, aircraft systems management has also been increasingly automated (refs. 4, 22, and 23).

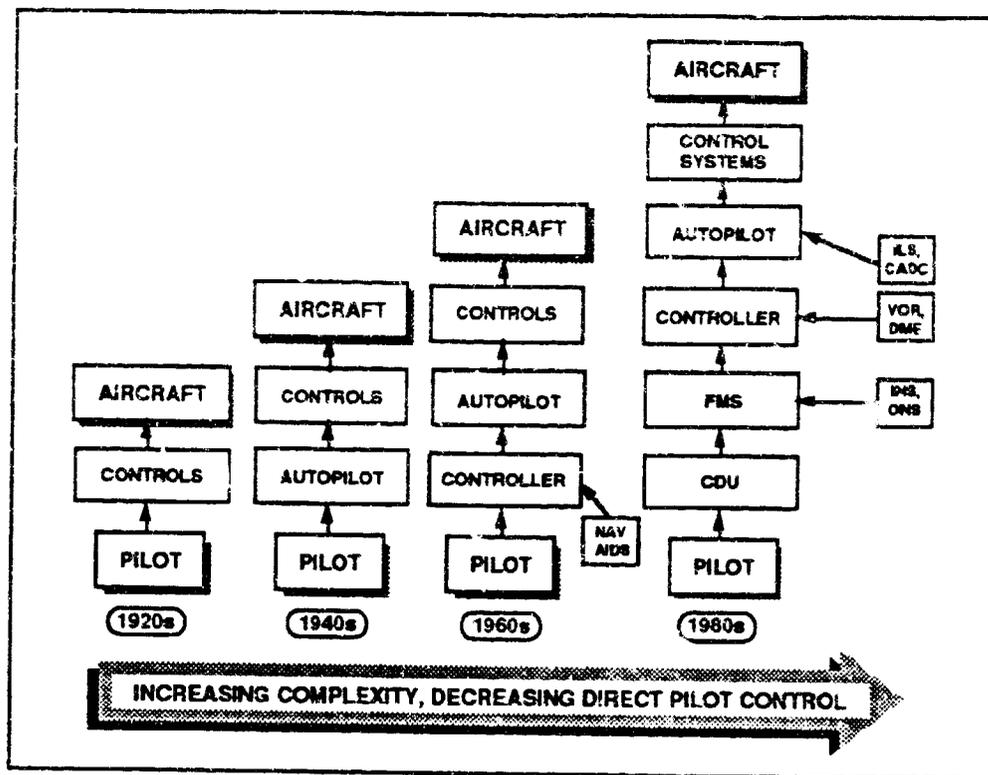


Figure 4: Increasing complexity of aircraft automation

The introduction of these automated devices and systems has improved system performance and has considerably simplified certain aspects of the piloting task, but it has also increased complexity in the cockpit (ref. 21). The versatility of contemporary autopilots has provided the pilot with many more modes of operation by which the aircraft can be controlled precisely, but it also requires that the pilot remain apprised of much more information about the automated systems (fig. 4). Contemporary flight management systems relieve the pilot of routine navigation chores but also require pilots to perform new programming and management tasks and to monitor system performance more closely. New displays have enabled the presentation of much more information regarding aircraft systems, state, and environmental factors, but they have also considerably increased the human operator's information processing load.

These trends toward more information, greater complexity, and more automatic aircraft operation have the potential to isolate the pilot from the vehicle and to decrease his or her awareness of the state and situation of the aircraft or system being controlled (ref. 24). This can occur either because of information overload, leading to channeling of attention and failure to perceive all relevant information, or because redundant perceptual cues have been reduced. It has become necessary to ask whether the richness of the information supplied to the pilot and the complexity of the automation (or at least its perceived complexity, from the viewpoint of the pilot), makes it less likely that the pilot will remain fully in command of the situation.

Humans cannot assimilate very large amounts of raw information in a short period of time, nor can they handle tasks of great complexity under tight time constraints. A major objective of this document is to facilitate discussion of how much information or complexity is too much. Another is to explore how increasingly complex information processing and control tasks can be simplified so as to remain within the capabilities of the persons who must perform them.

A third objective is to consider how much automation is necessary, and why. If systems are sufficiently simple (and this should always be a design goal), automation may not be needed. If tasks cannot be simplified, or are so time-critical that humans may be unable to perform them effectively, automation must be utilized. Even then, simpler automation will permit simpler interfaces and better human understanding of the automated systems. In particular, the structure or architecture of automation tools must be simple enough to permit them to be effectively managed by the human operator (fig. 5).

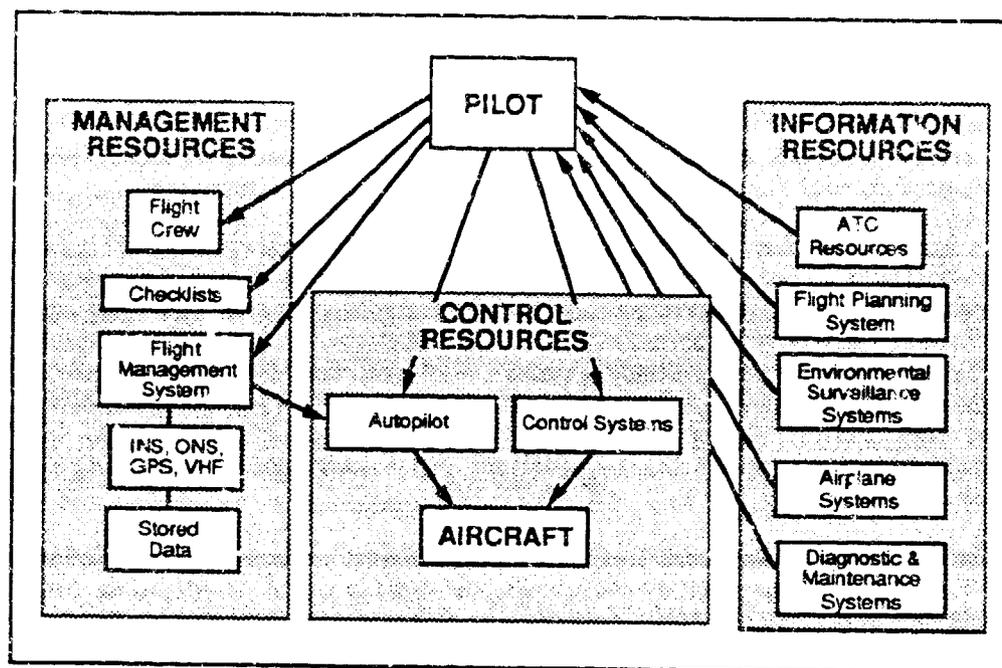


Figure 5: A construct of aircraft automation

A Concept of Human-Centered Automation

"Human-centered automation" is a systems concept. Its focus is a suite of automated systems designed to assist a human operator/controller/manager to accomplish his or her responsibilities. The quality and effectiveness of the pilot-automation system is a function of the degree to which the combined system takes advantage of the strengths and compensates for the weaknesses of both elements. To bound this concept, a fully autonomous, robotic system is not human-centered, by definition. The human has no critical role in such a system once it is designed. Conversely, a fully manual system contains no automation. None of today's complex human-machine systems is at either extreme, however; nearly all provide automatic devices to assist the human in performing a defined set of tasks, and reserve certain functions solely for the human operator. Our concern is with these partially automated systems in which humans play a central and, in the case of aviation, a commanding, role.

The Role of the Human in Highly Automated Systems

We have already inferred that current aircraft automation is able to perform nearly all of the continuous control tasks and most of the discrete tasks required to accomplish a mission. Why, then, is the human needed in such a system? Could automation to accomplish the rest of the tasks not be constructed? Would it not be easier and even cheaper to design highly reliable automata that could do the entire job without worrying about accommodating a human operator?

Under optimal circumstances, the "mechanical tasks" of getting an aircraft from one point to another could be accomplished automatically. The aviation system, however, is not an optimal, fully controlled system. Many variables within that system are highly dynamic and not fully predictable (the severity and movement of weather systems are prime examples). Aircraft themselves, while very reliable, sometimes fail in unpredicted and unpredictable ways, as was seen in the catastrophic engine failure of a United Airlines DC-10 at Sioux City in 1989 (ref. 25), the structural failure of a United 747 cargo door the same year (ref. 26), and the fuselage failure of an Aloha Airlines 737 over Hawaii in 1989 (ref. 27).

Automation can also fail in unpredictable ways. Minor system or procedural anomalies can cause unexpected effects that must be resolved in real time, as in an air traffic control breakdown in Atlanta terminal airspace in 1980 (ref. 28). These effects are complex; some are poorly understood. Even if the effects themselves could be predicted and modelled, the computational engine that can cope with such state variability in real time has not been constructed.

Though humans are far from perfect sensors, decision-makers and controllers, they possess three invaluable attributes. They are excellent detectors of signals in the midst of noise, they can reason effectively in the face of uncertainty, and they are capable of abstraction and conceptual organization. Humans thus provide to the aviation system a degree of flexibility that cannot now, and may never, be attained by computational systems. They can cope with failures not envisioned by aircraft and aviation system designers. They are *intelligent*: they possess the ability to learn from experience and thus the ability to respond quickly and successfully to new situations. Computers cannot do this except in narrowly defined, well understood domains and situations (refs. 29 and 92).

The abilities of humans to recognize and bound the expected, to cope with the unexpected, to innovate and to reason by analogy when previous experience does not cover a new problem are what has made the aviation system robust, for there are still many circumstances, especially in the weather domain, that are neither directly controllable nor fully predictable. Each of these uniquely human attributes is a compelling reason to retain the human in a central position in aircraft and in the aviation system.

Principles of Human-Centered Automation

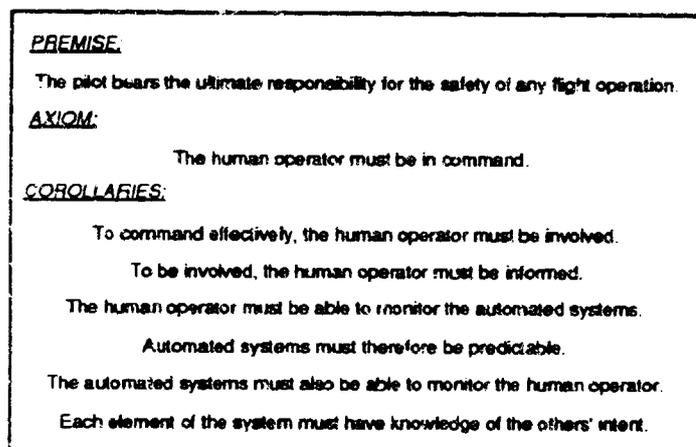


Figure 6 summarizes our view of human-centered aircraft automation. We assume that the human operator will continue to bear the ultimate responsibility for the safety of flight operations (ref. 6). Federal Aviation Regulations confer on the pilot in command essentially unlimited authority to permit him or her to fulfill this ultimate responsibility. This is axiomatic in civil aviation. We believe that certain corollaries devolve from this axiom. They are described briefly here and discussed in more detail in the Guidelines (section V).

Figure 6: First principles of human-centered aircraft automation

- *To command effectively, the human operator must be involved.*

To remain in command of a vehicle, operation, or situation, the commander must be involved in the operation. He or she must have an active role, whether that role is to control the aircraft directly or to manage the human or machine resources to which control has been delegated.

- *To be involved, the human operator must be informed.*

Without information about the conduct of the operation, involvement becomes random. The commander must have a continuing flow of information concerning the state and progress of the operation or system to maintain involvement with it. The information must be consistent with the command responsibilities of the pilot; it must include all data necessary to support the pilot's involvement in the operation.

- *The human operator must be able to monitor the automated systems.*

The ability to monitor the automated systems is necessary both to permit the pilot to remain "on top of" the situation, and also because automated systems are fallible. Flight-critical digital computers, in particular, are likely to fail in unpredictable ways at unpredictable times.

- *Automated systems must be predictable.*

The human commander must be able to evaluate the performance of automated systems against an internal model formed through knowledge of the normal behavior of the systems, if monitoring of them is to be effective. Only if the systems normally behave in a predictable fashion can the human operator rapidly detect departures from normal behavior and thus recognize failures in the automated systems.

- *The automated systems must also be able to monitor the human operator.*

Humans, of course, are not infallible either, and their failures may likewise be unpredictable, although a good deal has been learned about human failure modes. For that reason, it is necessary that human as well as machine performance be monitored. Many automated monitoring devices are in use in aviation today, but the availability of highly capable computers with access to much of the needed information makes it possible to consider doing more, in a more systematic fashion, to monitor pilot performance than has been done to date.

- *Each element of the system must have knowledge of the others' intent.*

Cross-monitoring can only be effective if the monitor understands what the operator of the monitored system is trying to accomplish. To obtain the benefits of effective monitoring, the intentions of the human or automated systems must be known; this applies equally to the monitoring of aircraft by humans on the ground, and the monitoring of air traffic control by pilots in flight.

II: AUTOMATION: PAST, PRESENT AND FUTURE

Introduction

In this section we look at automation that has been used in the past. We discuss some of the ways in which automation has been characterized, using the functions that a pilot must perform as a base. We examine automated systems that have worked well and some that have not been as successful, and attempt to draw from these examples issues that need to be considered by designers and operators. Finally, we attempt to project current automation technology into the future in the hope of discerning new developments that may pose new or additional questions regarding the roles, functions and forms of automation technology in the next generations of aircraft. The emphasis is on forming the questions that should be considered in specifying and designing automated systems. Section III examines pertinent characteristics of the environments in which automation will be applied, and the people who must operate automated systems.

Aircraft Functions

The range of functions that an airplane can perform is really quite limited. An airplane, properly controlled, can move about on a prepared surface. It can depart from that surface and once above the earth, in the atmosphere, it has freedom of motion in all spatial axes. Finally, it can return under control to a precise area on the earth's surface, land, and again move about on a prepared surface, coming to rest at a predetermined spot. All of the sophistication of current aircraft is devoted to insuring that this limited range of functions can be performed with complete reliability and safety.

All aircraft controls and systems are devoted to the performance of this narrow range of functions. Fadden's (ref. 30) taxonomy is very useful. *Control automation* assists or supplants a human pilot in guiding the airplane through the maneuvers necessary for their safe performance. If aircraft flew only under visual meteorological conditions over familiar routes between familiar airports, experienced pilots would need only very simple, straightforward automated devices to assist them in performing their missions.

Control automation includes devices devoted to the operation of aircraft subsystems, which are quite complex in modern aircraft. These systems control fuel, hydraulic power, alternating and direct current electrical power, pneumatic engine and anti-icing systems and pressurization, landing gear and brakes, and sometimes other functions.

Much of the automation found in contemporary aircraft is not devoted to controlling the aircraft, but rather to informing the pilots about the airplane's state and location and the location of real or imaginary sites on the surface of the earth. Fadden has called this "*information automation*." It includes all of the displays and avionics devoted to navigation and environmental surveillance, and also digital communications with air traffic control and airline operations. Information automation is expanding rapidly at this point in time; the next generation of transport aircraft may incorporate electronic library systems containing much of the data now stored on board in hard-copy form.

A third category can be added to this automation taxonomy, which one could call "*management automation*." This term denotes automation which permits the pilot to *manage* the conduct of a mission. Roughly speaking, management automation permits the pilot to exercise strategic, rather than simply tactical, control over the performance of a mission. In this sense, management refers to *goal-directed* rather than function-directed behavior. The pilot establishes a set of goals; management automation directs control automation in the performance of the required functions and directs information automation to keep the pilot informed of the state of the airplane and of progress toward satisfying the specified goals.

The pilot's control and management tasks, assisted by these categories of automation, may be considered as an hierarchy of closed loops, as shown in figure 7. The principal difference in those tasks as one proceeds from inner loop to outer loop is one of bandwidth; control automation relieves the pilot of the high-bandwidth requirements of direct aircraft control. Management automation decreases the bandwidth requirements still further. The amount and type of information required by the pilot also changes dramatically.

Note in this figure that the system is not an entirely closed loop. Open loop forcing functions include requirements imposed by the environment, by air traffic control, and by operator (company) requirements. Note also that each row of the diagram introduces additional displays which increase the information that must be attended to by the pilot.

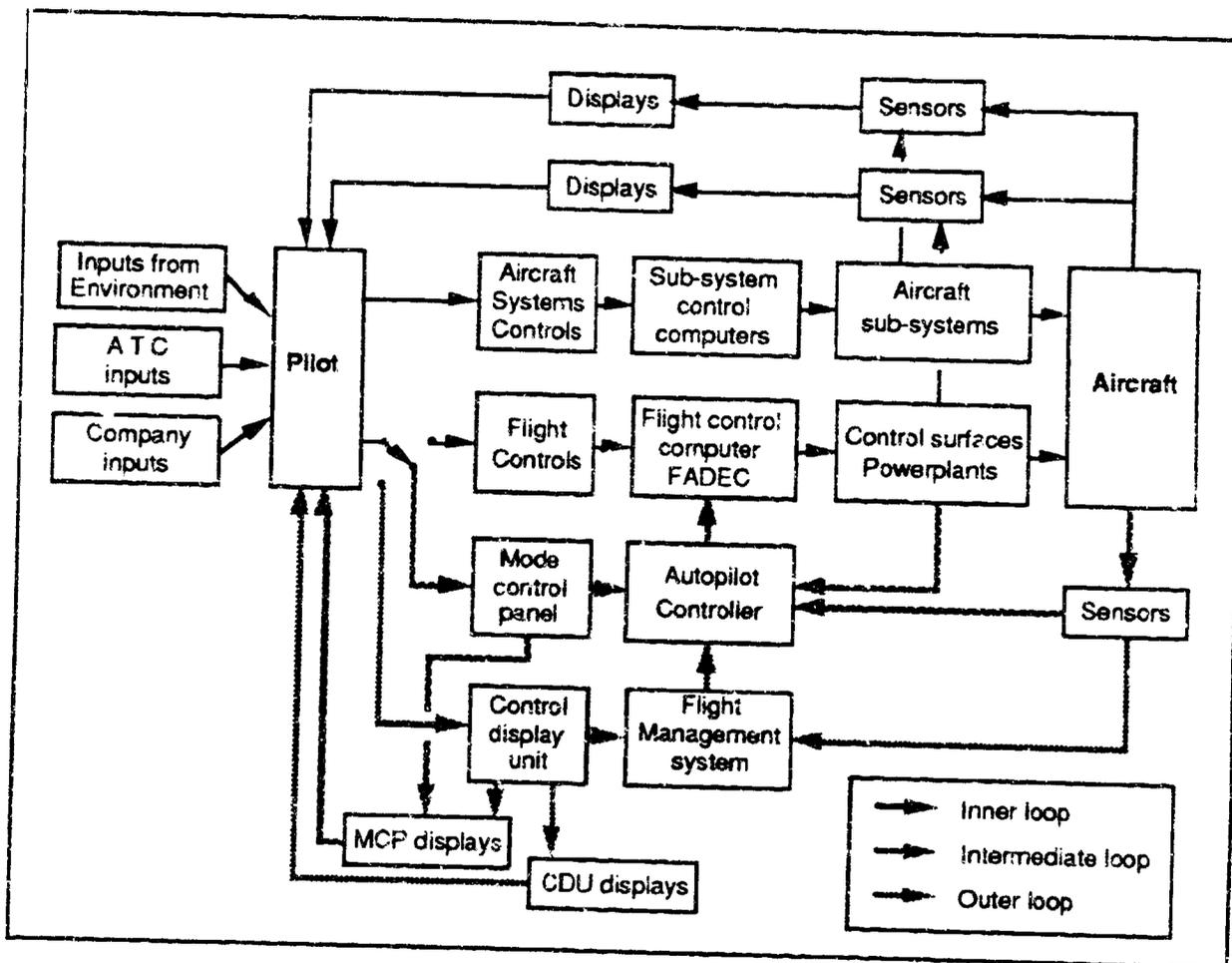


Figure 7: Control and display loops

Mission Functions

As inferred above, much of the complexity of modern automation relates not to the realization of basic aircraft capabilities but to the performance of the missions required of them in a wide range of environments. Within its fuel range, a modern airplane must be able to fly in nearly all kinds of weather, night or day, in airspace containing other aircraft, from any airport to any other airport, safely and efficiently, carrying passengers or cargo. It must be capable of taking off or landing under less than perfect environmental conditions on surfaces that are likewise less than perfect, and

must avoid terrain and other aircraft throughout its flight, all the while observing airline and air traffic control constraints.

This complex assignment introduces new elements into the equation. Pilots must be informed of where they are, where their destination is, and the existence of environmental threats including terrain, weather and other aircraft. They must know the state of their airplane, its systems and its consumables at all times. All of the things they need to know are dynamic and to some extent unpredictable, though the time constants vary; changes in any of them can affect the mission and require the establishment of new goals and the performance of new or different tasks.

Keeping track of all of this information can tax the capabilities of even highly proficient pilots. Though aircraft today are easy to fly, pilots must keep track of much more than simply the flying task. Herein lies one of the major challenges of aircraft automation. Properly designed and used, automation can assist its human masters in performing, simultaneously, the many information-gathering, cognitive, and management, as well as control, tasks required for the reliable performance of their missions. Figure 8 characterizes the range of information management tasks required for mission fulfillment.

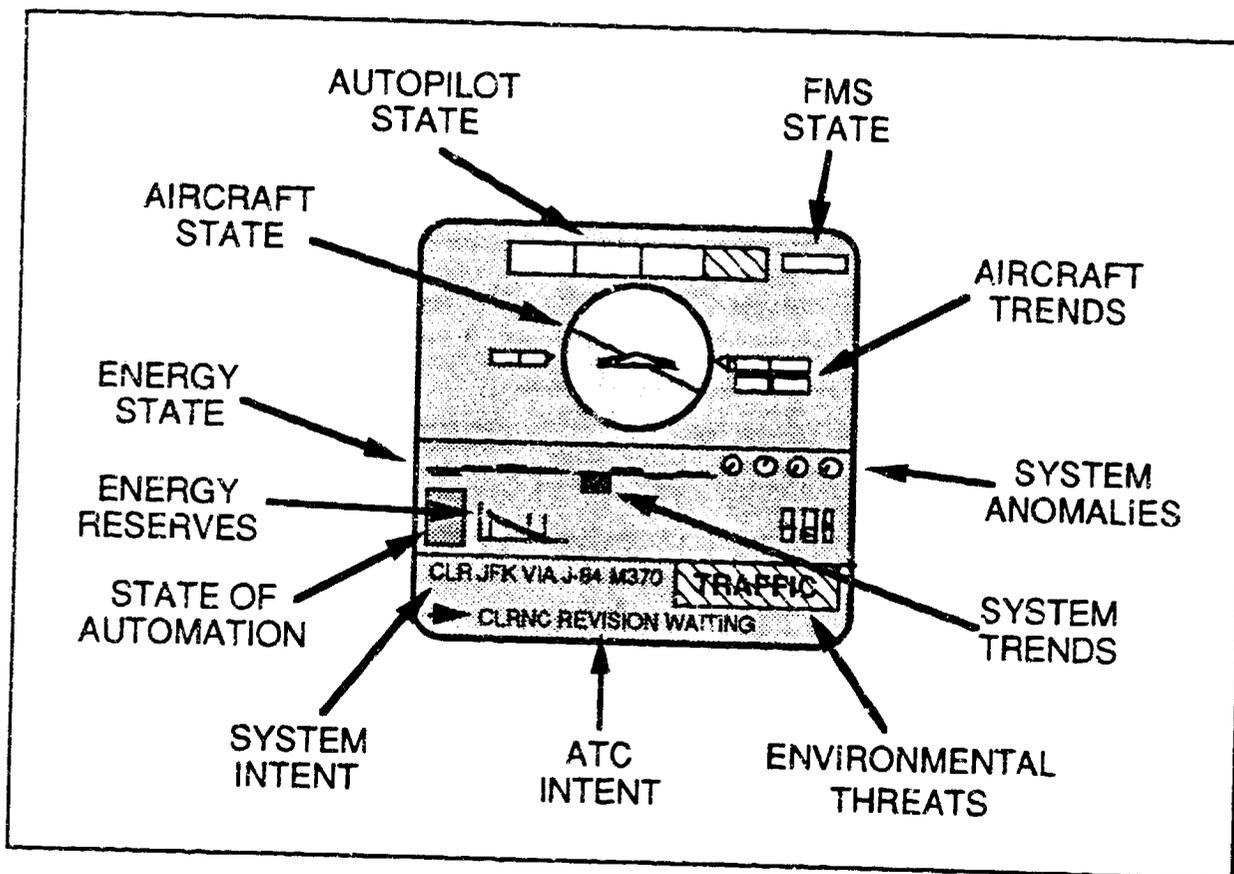


Figure 8: Pilot information requirements

The Tasks of the Pilot

The tasks pilots must perform are threefold. They must *maintain control* of their airplane, whether directly or through intermediate agents. They must *remain informed* of its state and position, of where they are going, of the environment through which they are flying, and of threats to successful mission accomplishment. Finally, they must *communicate* with air traffic control, their company, and sometimes other aircraft. An old training homily summarizes these tasks as "aviate, navigate, communicate." Though these are so fundamental as to be truisms, the Eastern

Air Lines L1011 that crashed in the Everglades did so because of a failure to maintain surveillance of the airplane's flight path while on autopilot (ref. 31). A DC-8 crashed at Portland after running out of fuel because the flight crew was preoccupied with preparations for an emergency landing (ref. 32). Many "controlled flight into terrain" accidents have occurred because of failure or inability to maintain positional awareness. The worst accident in air carrier history, the collision of two 747s at Tenerife, occurred because of a failure to communicate unambiguously (ref. 33).

These three tasks are simple enough when decomposed, but they can create severe workload burdens when performed simultaneously under demanding conditions. Such conditions are often not of the flight crew's making; figure 7 indicates that there are open-loop forcing inputs from air traffic control, from airline companies, and from the environment. Automation can lighten this burden on pilots, first by relieving them of the burden of inner-loop control, second by providing integrated information, and third by allowing them to manage at a higher level. The figure also suggests, however, that each of these kinds of automation increases the information processing burden upon pilots, by requiring them to keep track of additional systems and data. Thus, while automation has decreased the bandwidth of pilots' tasks, it has increased mental (perceptual and cognitive) demands upon them. It has also increased the "overhead": the knowledge and information necessary to operate the automation itself.

An automation paradox: Herein lies a paradox of aircraft automation. To the extent that it has taken over inner and intermediate loop tasks, it *has* changed the tasks of the pilot, notwithstanding the conclusions of the President's Task Force on Crew Complement. Whether it has lightened them depends to a considerable extent on the demands of the task, and on the amount of information and attention required to operate and monitor the automated systems and displays. It has been observed (refs. 19 and 34) that automation may decrease workload when it is already comparatively low, during cruise flight and at high altitude, but that it may increase workload when it is already high, during climbing or descending flight in terminal areas. It should be noted immediately that it is not clear whether this is an inherent automation problem, or whether this is because we have not provided simple enough interfaces through which pilots interact with automation. In short, have we automated the wrong things, or have we simply done an inadequate job in some of our efforts to implement higher levels of automation in a simple enough manner?

The point of this discussion is that our information concerning the effects of automation, and particularly its unwanted effects, does not usually differentiate between "good" automation, poorly implemented, and "bad" automation, in terms of roles and functions. It is critical that these be differentiated in any discussion of automation, and we shall try to keep this difference in mind as we proceed to a discussion of the automation that has been developed to date.

Control Automation

Here we will describe automation that has been implemented in transport aircraft to date. This list is not exhaustive, but it attempts to place new automation in the context of increasing requirements and in the context of other enabling technology. Figure 9 illustrates the control aspect of the pilot's task.

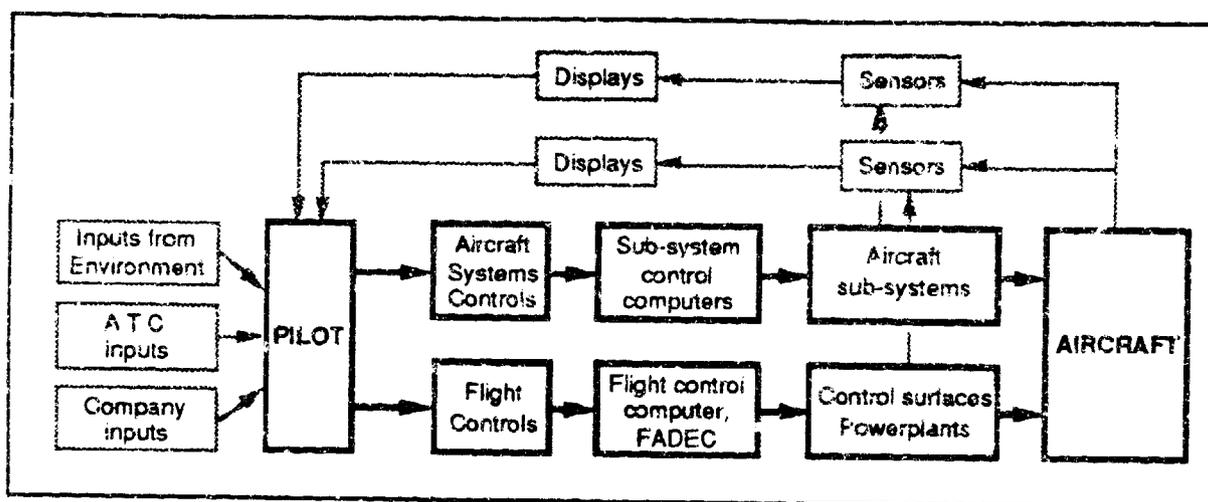


Figure 9: Control automation

Flight path control: As indicated in the introduction, control automation has been around for a long time. The first automated controllers simply maintained attitude in the roll axis; later generations of such devices have been called "wing levelers" and they continue to be available for general aviation aircraft today. Originally introduced to ease pilot workload in flying extremely unstable airplanes, they still perform that function, though aircraft stability has improved dramatically. Autopilots, as such devices came to be called, added other axes of control; the device used in the world flight of Post's *Winnie Mae* was a three-axis device which maintained the aircraft in pitch, roll and yaw, the three inner-loop functions required (ref. 2).

In the early generations of autopilots, the gyroscope which sensed roll and yaw was also used as a heading, or directional, gyro in the cockpit. Sensors in this device permitted a constant heading to be specified by the pilot and held by the autopilot, though the gyroscope was subject to precession and its directional component had to be reset frequently by reference to the aircraft magnetic compass. Some autopilots of this period later incorporated a relative barometric altitude sensor which could be used to hold altitude as well, once the proper altitude was attained and indicated to the sensor. In these developments, we see the beginnings of intermediate loop control, in which the pilot was able to specify heading and altitude to be maintained, rather than simply roll and pitch attitude.

To go beyond these tasks required many years and the development of complex electronic devices. The advent of precision radio navigation systems capable of providing both azimuthal and distance information occurred during the late 1940s and early 1950s. Very high frequency (VHF) navigational radios eliminated problems due to radio frequency interference from thunderstorms, but they were limited to line-of-sight coverage. VHF omnidirectional range (VOR) transmitters became the foundation of the "common system" of aerial radio navigation. Distance measuring equipment (DME), consisting of airborne interrogators and ground transponders, was co-located with and augmented the information provided by VOR transmitters (figure 10).

For precision approach guidance, VHF high precision directional "localizer" transmitters (LOC) and ultra-high frequency glide slope transmitters (GS) were located on airport runways; together they formed the basis for the instrument landing systems (ILS) which are still the standard approach aids in the current system. DME has more recently been co-located with ILS as well as with enroute navigation aids.

These devices and specialized aircraft navigational radio receivers or transmitter-receivers (transceivers) provided aircraft with positional information of higher precision. Their signals provided unambiguous azimuthal and distance information, which could be used either by pilots or

by autopilots to provide intermediate loop control of aircraft paths. ILS signals, which provided height guidance as well, were used to permit both manual and automatic ("coupled") precision approaches to runways. They enabled the design and implementation of autopilots with a wide range of capabilities including maintenance of pitch, roll and yaw, maintenance of a track to or from a surface navigational aid, and the capture of localizer and glide slope centerlines followed by the conduct of automatic approaches.

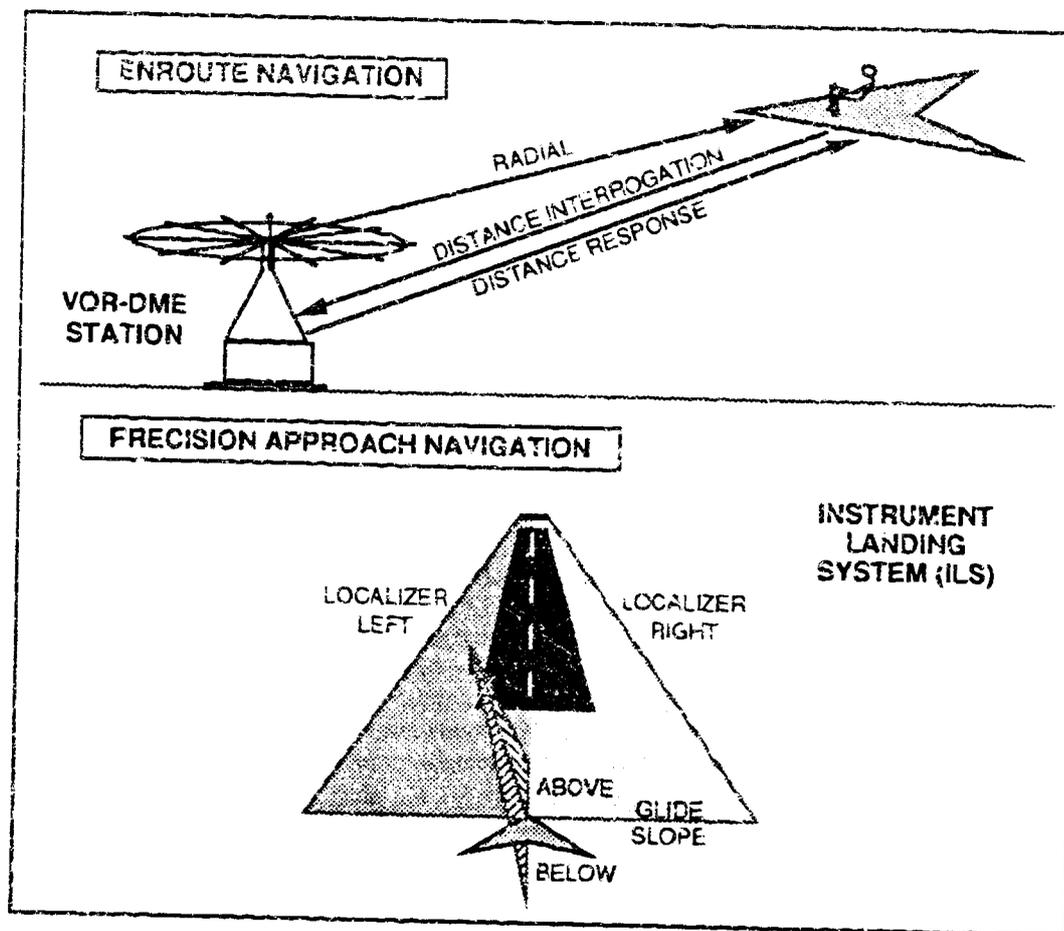


Figure 10: Precision enroute and approach navigation aids: VOR and ILS

Early autopilots with navigation couplers were disliked because of the roughness with which they handled station passage. (Navigation radials become very narrow as the station is approached and abrupt flight path changes often occurred.) If pilots used the navigation couplers at all, they tended to revert to heading control in the vicinity of VOR stations (ref. 35). Transport pilots take pride in providing their passengers with a smooth, comfortable ride; when automated devices were unable to do as well, they were simply turned off.

Air mass data were also required for control of aircraft speed and height. Barometric altimeters of extreme precision became the basis for control of height; precision air speed sensors were utilized for speed sensing and later, with the introduction of automatic throttle controls, for speed control. Central air data computers (CADC) were provided when jet-powered transport aircraft entered service in the 1950s; these devices provided integrated precision sensing of static and dynamic air pressure. The computer likewise made possible the differentiation of barometric altitude data and enabled precision climbs and descents.

Swept-wing jet aircraft are susceptible to adverse yaw during banked turns. Early jet transport aircraft (notably the Boeing KC-135 tanker) required very precise manual control to counter this

tendency. When the 707 derivative of the KC-135 was introduced, yaw dampers were provided to counter this problem. Though nominally under control of the pilot (they can be turned off), yaw dampers in fact operate autonomously in all jet aircraft. The same can be said of pitch trim compensators, used to counter the tendency of jet aircraft to pitch down at high Mach numbers. These devices, first introduced in the DC-8, likewise operate essentially autonomously.

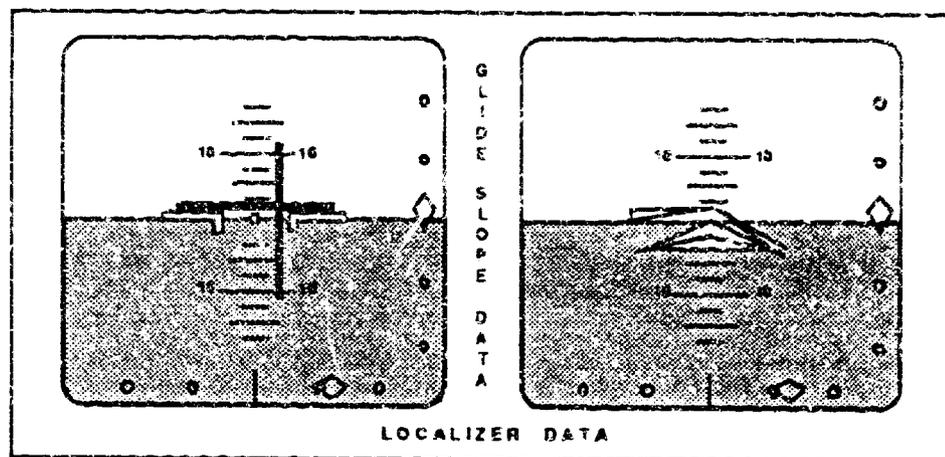


Figure 11: Dual-cue (left) and single-cue Flight Directors. Aircraft is left of localizer and just below glide slope; directors are commanding a right turn and climb to regain centerlines.

Swept-wing aircraft also required more precise control to compensate for decreased stability and higher speeds, particularly at high altitudes and during approaches to landing. Flight by reference to precision navigational data was made easier by the development of flight director displays which provided pilots with computed pitch and roll commands, displayed as shown in figure 11. The directors were much easier to fly than unmodified VOR or localizer and glide slope data, which were presented on the periphery of the same instruments used for the director displays. Such displays rapidly became a mainstay of transport aviation; they made it possible for pilots of average ability to conduct maneuvers with high precision, though concern was expressed about "losing sight of raw data" while relying upon the directors for guidance. A Delta Airlines DC-9 impacted a sea wall short of runway 4R at Boston during an approach in severely limited visibility (ref. 36); its crew is believed to have followed the flight director which was set in "attitude" mode rather than "approach" mode, without adequate cross-checking of localizer and glide slope data.

Control of aircraft longitudinal and lateral trim is maintained by several means, including small trim tabs on control surfaces. Automatic trim control devices which operate either on these surfaces or on the aircraft control system have been components of autopilots for many years. Most operate autonomously in certain autoflight modes. Some newer aircraft with advanced primary flight control systems incorporate a load factor demand law which continuously trims the aircraft toward a 1 G condition. This relieves the pilot of the task of retrimming the airplane after power changes, but it also removes tactile feedback regarding longitudinal trim. Other aircraft, which incorporate fuel shifting to minimize aerodynamic drag by adjusting aircraft center of gravity, also trim the airplane to minimize pilot attention to the load shifting. Most of these devices require no pilot input or attention under normal conditions.

Spoilers, aerodynamic surfaces on the wing long used in gliders to moderate flight path during approach to landing, were installed on jet aircraft to increase control authority and reduce adverse yaw, to assist in slowing these aerodynamically clean aircraft, to permit steeper descents and to dump aerodynamic lift during landings. Though early jets had manually-controlled spoilers, later generations had spoilers that were activated either manually, in flight, or automatically by main wheel spin-up during landings. The Lockheed L1011-500 incorporated a sophisticated system known as direct lift control for automatic precise flight path control during automatic approaches.

Some of the newest transports also incorporate automatic gust alleviation control using spoilers. The newest aircraft also provide automatic spoiler operation if power levers are pulled fully back during an aborted takeoff, and may apply autobraking when ground spoilers are deployed.

Some aircraft now in service (A320) incorporate "fly-by-wire" instead of conventional mechanical or hydraulic control systems. In fly-by-wire systems, the pilot's controls actuate electronic control devices whose outputs are directed to hydraulic or electrical servomechanisms; these devices actuate the control surfaces. The advent of fly-by-wire systems has provided control system engineers with great flexibility to tailor the control responses to match desired characteristics. An inherently unstable airplane can be made to feel, to the pilot, like an extremely stable platform, and indeed, some of these aircraft deliberately incorporate a degree of reduced longitudinal stability, which is compensated for by a stability augmentation system. Even manually-controlled flight in such aircraft is actually accomplished by one or more computers interposed between the pilot and the machine.

This control architecture offers other opportunities to the designer, who may now limit the flight envelope, provide precisely tempered degradation of flying qualities as safe operating limits are approached, or simply render it impossible for the pilot to exceed certain boundaries. These strategies are usually referred to as "envelope protection," though the latter strategy could more appropriately be termed "envelope limitation." One issue of importance is the effect on the pilot, over time, of this "shift in responsibility" from the pilot to the "system." If the pilot believes he or she is protected from control errors, will he or she be less mindful of safe operating limits? The implications of these changes in the allocation of functions require discussion (see p. 29-30).

It is likely that most or all future large transports will incorporate fly-by-wire (or fly-by-light, using electro-optical conduits for control signals) as does the A320. Along with fly-by-wire systems has come a considerable increase in the flexibility of autopilot and flight management systems. The newest systems have a great many modes of operation, each of which must be understood by the pilot if they are to be used appropriately.

Power control: Reciprocating engine aircraft had only limited inner-loop automation of control systems. Automatic mixture controls which utilized barometric altitude data to adjust fuel-air ratios were installed in the DC-3 and later transports. Automated control of propeller pitch was introduced during the 1930s, not long after controllable-pitch propellers. Later multi-engine aircraft required precise synchronization of propeller speeds to minimize vibration and annoying beat frequency noise; propeller autosynchronizers were developed to match the propeller speeds of all engines. Throttles, propeller and mixture controls were not integrated, however, until the recent introduction into general aviation of a Mooney airplane powered by a new Porsche engine incorporating a single power controller.

Following world war II, surplus military aircraft were purchased in considerable numbers by civil operators. They thus required civil registration to standards quite different from those imposed by the armed forces in the heat of war. Some of these aircraft had undesirable flying characteristics under some circumstances. In particular, some were extremely demanding to fly after an engine failure at low speed during or shortly following takeoff. To ease the asymmetric drag caused by a windmilling propeller and assist pilots in maintaining control during the critical moments after takeoff, automatic propeller feathering systems were introduced in some aircraft. These devices sensed a loss of thrust in a malfunctioning engine and rapidly moved its propeller to a fully feathered position. The devices provided critical assistance when they functioned properly, but several accidents occurred after fully functional engines were shut down autonomously. There have also been accidents, such as that of an Aerospatiale Nord commuter airplane at Los Angeles, in which pilots have shut down the remaining engine after an autofeathering system has operated to make the other, malfunctioning engine ineffective (ref. 37). Autofeathering systems, once armed by pilots, are independent of pilot control and they do not notify the pilot before taking action. To that extent, they remove a portion of the pilot's authority, a topic on which more will be said later.

The earliest autothrottle systems in turbojet transports simply controlled fuel flow to turbojet engines. They were relatively crude and were not liked (or much used) by pilots because of the roughness of their power control (which disturbed passengers). Later devices, more sophisticated controllers and better powerplant models improved the operation of autothrottle systems. More recently the development of full-authority digital engine controllers (FADEC) has improved still further the precision with which jet powerplants can be controlled. Nearly all contemporary jet aircraft incorporate autothrust systems which are used to set engine power to automatically-determined parameters even during the takeoff roll.

Landing gear: Landing gear retraction and extension is still a manual procedure in all transport aircraft, but information automation in the form of configuration warning systems has been used since it was first discovered by a hapless pilot that retractable gear aircraft could be landed with the gear retracted. Most such systems have provided a warning if throttles were pulled back. The use of idle power routinely during descents in jet aircraft required that the landing gear warning system be modified to take account of barometric altitude or other factors that could indicate that landing was not contemplated at the time. Aircraft without such modifications provided large numbers of nuisance warnings to pilots. In an imaginative attempt to circumvent the problem of gear-up landings, the Piper Aircraft Company developed and installed an automatic gear-lowering device on its *Arrow* series of general aviation aircraft. The device used a simple pitot mounted in the propeller airstream to sense reduced power and air speed. It worked autonomously and effectively, but it also required the pilot to exert continuous pressure on a bypass switch to prevent gear extension during intentional low-speed maneuvers at altitude, a difficult task when both hands were required for aircraft and power control.

Virtually all jet aircraft have anti-skid or anti-lock braking systems, in which wheel rotational speed is sensed and used to modify brake application. Newer generations of transport aircraft also incorporate automatic braking upon wheel spin-up. The braking force is chosen by the pilots prior to landing; brake application using the selected schedule is then automatic.

Aircraft subsystems: In early generations of jet aircraft, the many aircraft subsystems were operated in the conventional way, with switches in the cockpit controlling most aspects of system operation. Three-person flight crews included a flight engineer whose primary task was the operation and surveillance of these systems: electrical, hydraulic, pneumatic and fuel systems. In some aircraft designed for a crew of two persons, attempts were made to simplify system operations somewhat to decrease flight crew workload. Seat belt and no smoking signs were activated automatically; automatic load shedding was introduced to simplify electrical system reconfiguration following a generator failure; air conditioning pack deactivation was automatic following an engine failure on takeoff, etc. These and other measures represented a piecemeal approach to the problem, however; subsystems were still considered in isolation by designers, and until recently, system operation during failures was still complex.

The DC9-80 (now designated the MD-80) introduced a somewhat simpler architecture and more subsystem automation in 1980 (ref. 38). The Boeing 767/757 series of aircraft incorporated simplified procedures and a structured "need-to-know" concept in its information automation. An engine indicating and crew alerting system (EICAS) provided pictorial and alphanumeric information on cathode-ray tubes (CRT) in the cockpit. Pilots were informed by alphanumeric messages of failures that required crew action; the aircraft "Quick Reference Handbook" (QRH) provided the required actions in checklist form. The "do" lists were also considerably simplified (ref. 39).

When the Airbus A310 was introduced, it incorporated an electronic centralized aircraft monitoring system (ECAM). This system provided synoptic diagrams of aircraft subsystems which displayed system condition in pictorial form on cathode ray tube (CRT) screens (ref. 40). Paper checklists were still used to handle faults, which were annunciated in alphanumeric form on

a separate screen. The later A320 had a very similar system. In the 747-400, the first 747 model designed for a crew of two persons, Boeing incorporated system synoptics into its EICAS system, while retaining alphanumeric alerting messages and paper checklists that informed pilots of all actions to be taken following an annunciated condition, as in its 767/757 types (ref. 22).

The Douglas Aircraft Company took a somewhat different direction in its MD-11, introduced in 1990 (ref. 4). The MD-11 is a very long-range derivative of the very successful DC-10, but with a radically redesigned two-person cockpit. Douglas cockpit designers were very concerned about lightening pilot workload; their task and workload analyses indicated that major decreases in workload could be achieved by automating aircraft subsystem operations. To quote Douglas' chief of MD-11 operations, "One of our fundamental strategies has been: if you know what you want the pilot to do, don't tell him, do it" (ref. 41). Many normal subsystem functions formerly performed by the flight crew have been automated; handling of faults is also largely automatic.

The MD-11 engine and alert displays (EAD) are superficially similar to the systems described above, but the subsystem management approach is markedly different. Most subsystem reconfiguration following component malfunctions or failures is automatic. Pilots are informed with an alert; they may cancel the associated alerting message by selecting and viewing the appropriate synoptic. This action is not required immediately, however, since the appropriate actions have already been taken. Paper checklists are still used as a reminder of required flight crew actions.

The Boeing 777, now in design, will incorporate electronic checklists with some level of automatic sensing of checklist items (ref. 5). It will remind pilots of skipped actions and will permit the crew to skip back and forth between checklists if required because of multiple failures.

Discussion of Control Automation

Flight path control: Control automation has a long and honorable history. Most aspects of control automation are well understood and are not controversial. Taken singly, most automated flight control systems are based on comparatively simple models that can be explained fairly easily to pilots. The behavior of these systems is predictable. Information concerning the actions of the automation is observed in airplane behavior, this information is usually, though not invariably, sufficient to maintain pilot involvement. It is also usually sufficient to permit the pilot to monitor the behavior of the automation. Problems in monitoring control automation have occurred when the devices were behaving reasonably, but incorrectly (as in the SAS DC-10 accident at New York, ref. 15), or when pilots were not alert, for whatever reasons, to the state of the automation (the China Airlines 747 mishap near San Francisco, ref. 14). Control automation data to this time are only beginning to be used to monitor or circumscribe pilot behavior (see discussion of envelope protection and limitation, page 29).

Pilot responses to and use of these automated flight control devices and systems have been studied thoroughly. They have not found most such devices to be difficult to understand or use effectively, though the proliferation of control modes in the newest fly-by-wire systems poses many more potential problems than did earlier generations of control automation in which the pilot was more directly coupled to the control surfaces. In the past, as an instance, the large-displacement control yokes used by the two pilots were directly and physically coupled; they were also coupled to the automation and thus moved perceptibly when the autopilot made control inputs.

In the Airbus A320, small-displacement sidestick controllers are installed; they are not cross-coupled, and inputs by one pilot are not visible or tactually perceptible by the other. A fairly complex mixing algorithm, a lockout device and visible indicator lights are provided to assist the pilots in knowing who is in control and to what extent. It should be mentioned that the C* control law used in this airplane is not speed stable, so different feedback loops may be required. Autopilot control inputs are not fed back to the sidesticks. The lack of tactile feedback between the

sidesticks is not known to have presented problems thus far, but it has led to questions regarding the usefulness of such feedback in transport aircraft

The large number of control modes in highly automated aircraft has also been of concern. The A320 autopilot "open descent" mode, and its coupling to the flight director system of the airplane, may have been a factor in the Indian Airlines landing accident at Bangalore, in that there appears to have been a late recognition on the part of the flying pilot regarding the need to switch both directors to another mode prior to the final approach (ref. 13). Incident reports have documented similar occurrences with earlier recovery. This mode, like all others, is annunciated in text on the flight mode annunciation panel; the problem rather appears to be a lack of understanding of a relatively complex, highly integrated set of automated systems and of their interactions. Air carriers operating the A320 have instituted procedures designed to prevent open descent below a safe transition altitude on final approach, but it must be asked whether procedural approaches to such problems are as effective as designs that are easier to understand or that are not susceptible to misunderstanding.

Error resistance and error tolerance: System modes such as this necessitate a consideration of human error in the operation of such systems. It is known that human errors will occur; such errors are contributory factors in roughly two-thirds of air carrier accidents. Indeed, a desire to minimize such errors has been a part of the rationale for the implementation of advanced aircraft automation. At least two approaches can be taken to minimize the effects of human error. A system may be designed to be highly *error-resistant*; that is, to make it very difficult for the human to make an error in the operation of the system. Simplicity in system architecture and the provision of clear, unambiguous information on display interfaces are important tools with which to improve error-resistance. (See Nagel, ref. 42, for discussion of these concepts.)

Attacking the problem of human error by design of error-resistant systems is not enough, however; it is also necessary that system designs be *error-tolerant*, able either to trap errors or to mitigate their effects. Such error-tolerance can be strengthened by designing monitoring capabilities into the automation, as is done in configuration monitoring systems, or by introducing system envelope limitations, as is done in the A320 flight control system and several power control systems. The use of procedural controls as a substitute for designing inherently error-resistant and error-tolerant systems may be effective, but is less foolproof. In the case mentioned above, procedures have been evoked to make the system error-resistant, since it is not inherently error-tolerant. Both error resistance and error tolerance, discussed further in section IV, must be paramount aims of the cockpit design team.

Power control: The A320 also incorporates thrust levers that do not move when power is applied or withdrawn by the autothrust system. Visual ECAM displays indicate both power commanded and power delivered, but ancillary tactile or visible feedback is not provided by the levers themselves. This difference from previous aircraft has evoked fairly widespread concern in the operational community, though it should be said immediately that the concern does not appear to be manifested by airlines operating this aircraft type.

Based on limited operating experience to date, it appears that pilots are usually able to obtain all needed information concerning flight and power control either with, or without, tactile feedback of control movements instituted by the automatic systems. This may be a case in which there is not "one best way," based on empirical or analytical knowledge, to automate a system, and in which, therefore, any of several approaches may be effective, provided that pilots are provided with sufficient information to permit them to monitor the systems effectively. Unfortunately, information concerning the rare cases in which a particular innovation is *not* effective in providing adequate feedback may not come to light unless a mishap occurs. Research into the proper complement of control and monitoring functions for automated cockpits is badly needed.

Aircraft subsystems: Automated flight control systems usually provide immediate feedback to pilots concerning their continued functioning. Feedback concerning aircraft subsystem status may be much less obvious. Older three-person aircraft incorporated a multiplicity of lights and gages to provide the flight engineer or pilots with such information; cockpit automation and simplification efforts have attempted (with considerable success) to minimize the amount of system information which the crew must monitor. The provision of simpler interfaces, however, has not been due entirely to the design of simpler aircraft subsystems. On the contrary, system complexity in some cases has increased greatly. Where simpler interfaces reflect simpler subsystems, the benefits are obvious. When a simple interface hides a functionally complex system, there may well be covert problems waiting to emerge during a difficult emergency.

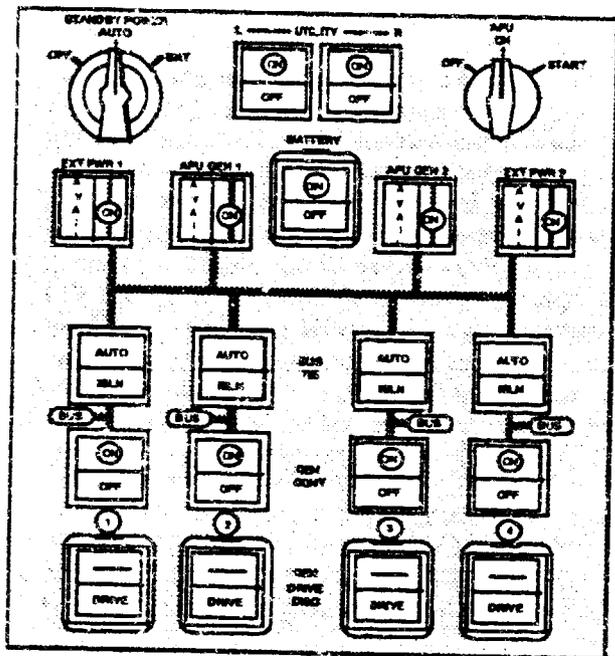


Fig. 12: Overhead panel, AC electrical system, 747-400.

Practices with respect to the provision of information regarding subsystems have varied, from the Boeing 767/757 "need-to-know" concept, to the provision of synoptics simply for pilot information in the 747-400 (figure 13), to synoptics that are the primary means of subsystem feedback in the MD-11 and A-310/320 types. The A320 also presents a limited number of normal checklists on its ECAM screens; a broader implementation of electronic checklists with automatic sensing of skipped actions is under consideration for the Boeing 777, now in design, and will likely be seen in many future transport aircraft. Such automation will permit the flight crew to alternate among several checklists when necessary to resolve compound faults, though automated prioritization schemes for such faults are under consideration by human factors researchers.

Cockpit simplification has included drastic reductions in the number of subsystem controls and also standardization of those controls, nearly all of which are now lighted pushbuttons with legends. Critical buttons may be guarded. The switches are usually located in subsystem diagrams (figure 12). The use of pushbuttons of identical shape and size in place of a variety of toggle switches has cleaned up the overhead panel, but it has made more difficult the location by feel of a given switch. Manufacturers state that their "dark cockpit" concept, in which buttons are lighted only if they require attention, indicates those that must be used, and point out that buttons should be actuated only after visual confirmation of which button to press. As noted above, Douglas Aircraft Co. has automated large segments of the subsystems management task (a backup manual mode is provided, and all switches necessary for subsystem control are on the overhead panel).

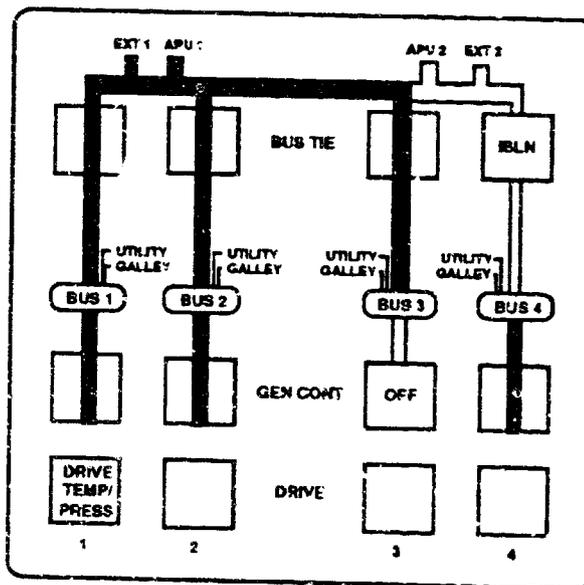


Fig. 13: Synoptic display for system shown in fig. 12.

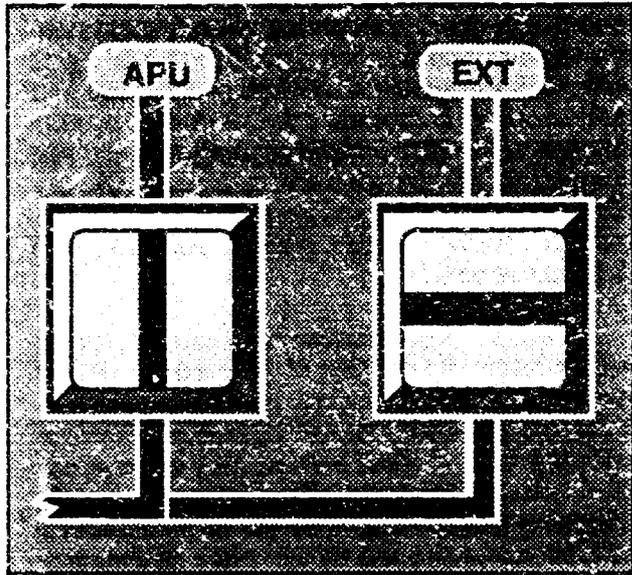


Fig. 14: Touch-sensitive screen switches on a CRT display

Research is underway on CRT screens on which subsystem synoptics containing "soft switches", touch-sensitive areas overlying switch depictions, would be depicted. Subsystem control would be affected directly through such screens, which would respond to switch actuations. The advantages and disadvantages of this approach can be hypothesized but are not yet clear. Dedicated panels in which switches are always in the same place permit memorization of switch locations and set patterns of behavior, but pushbutton switch legends contain small, sometimes cryptic alphanumeric legends, and presbyopic older pilots may have difficulty reading legends on the overhead unless they are fitted with special correcting lenses. Synoptic subsystem diagrams will require familiarity with a number of differ-

ent switch locations, distinct for each system depicted. The legibility of touch screens on the primary display panels should be considerably better, but operation of touch-sensitive switches may be more difficult in turbulence; they will also be farther from the pilots. Research will be needed to determine whether the potential advantages of "soft switches" outweigh their drawbacks.

The amount of aircraft status information that must be provided is a function of the human operator roles in mission accomplishment. If humans are expected to control aircraft subsystems, they must be given that minimum of information necessary to perform those tasks. If the subsystems are controlled autonomously and the human's only role is to remain cognizant of their status and the effects upon mission accomplishment, a quite different quantity and type of information concerning system status may be called for, though it is necessary in this case that the operator understand not only the system controlled but also the automation that is controlling it, so that automation failures can be detected. In this case, it may not be necessary that non-flight critical information be made available at all. For these reasons, it is necessary to consider the range of control and management options to be provided the pilots of advanced, highly-automated aircraft.

The control-management continuum: It is implicit in the above discussion that pilots may play any of a variety of roles in the control and management of highly automated aircraft. These roles range from direct manual control of flight path and all aircraft systems to largely autonomous operations in which the pilot's role is minimal. The development of highly capable automation makes it necessary to consider these roles in more depth. A control-management continuum is presented in figure 15 to facilitate this discussion (ref. 43).

None of today's aircraft can be operated entirely at either extreme of this spectrum of control and management. Indeed, an aircraft operated even by *direct manual control* may incorporate many kinds of control automation, such as yaw dampers, a pitch trim compensator, automated configuration warning devices, etc. Conversely, even remotely piloted vehicles are not fully autonomous; the locus of control of these aircraft has simply been moved to another airborne or a ground control station. Nonetheless, today's airplanes, and those of tomorrow as well, incorporate elements at or near the extremes, and the full range of options must be considered.

The ability to control an airplane without the assistance of automation must be demonstrated by any pilot before a type rating for that airplane can be issued, if the aircraft itself is certified for such operation. This includes the ability to handle the machine without even the automation aids,

such as yaw dampers, that normally operate full-time in an autonomous mode. That flying task, however, can be extremely demanding in a machine in which stability is relaxed and stability augmentation is provided by redundant, fail-operational systems.

	MANAGEMENT MODE	AUTOMATION FUNCTIONS	HUMAN FUNCTIONS
VERY HIGH	AUTONOMOUS OPERATION	Fully autonomous operation Pilot not usually informed System may or may not be capable of being disabled	Pilot generally has no role in operation Monitoring is limited to fault detection Goals are self-defined; pilot normally has no reason to intervene
	MANAGEMENT BY EXCEPTION	Essentially autonomous operation Automatic reconfiguration System informs pilot and monitors responses	Pilot informed of system intent Must consent to critical decisions May intervene by reverting to lower level
	MANAGEMENT BY CONSENT	Full automatic control of aircraft and flight Intent, diagnostic and prompting functions provided	Pilot must consent to state changes, checklist execution, anomaly resolution Manual execution of critical actions
	MANAGEMENT BY DELEGATION	Autopilot & autothrottle control of flight path Automatic communications and raw following	Pilot commands hdg, alt, speed; Manual or coupled navigation; Commands system operations, checklists, communications
	SHARED CONTROL	Enhanced control and guidance; Smart advisory systems; Potential flight path and other predictor displays	Pilot in control through CWS or envelope-protected system; May utilize advisory systems; System management manual
	ASSISTED MANUAL CONTROL	Flight director, FMS, nav modules; Data link with manual messages; Monitoring of flight path control and aircraft systems	Direct authority over all systems; Manual control, aided by F/D and enhanced navigation displays FMS is available; trend info on request
VERY LOW	DIRECT MANUAL CONTROL	Normal warnings and alerts provided; Routine ACARS communications performed automatically	Direct authority over all systems; Manual control utilizing raw data; Unaided decision-making; Manual communications

Figure 15: A continuum of aircraft control and management

Most flying today is *assisted* to a greater or lesser extent, if only by hydraulic amplification of control inputs. Flight directors, stability augmentation systems, enhanced displays, and in newer aircraft various degrees of envelope protection, assist the pilot in his or her manual control tasks. To some extent, pilots can specify the degree of assistance desired, but much of the assistance operates full-time and some of it is not intended to be bypassed. The pilot remains in the control loop, but it is an intermediate rather than the inner loop.

Whether pilots of limited experience should be required by regulation to have and demonstrate this level of manual control ability in today's airplanes, which incorporate highly redundant automated control assistance, is beyond the scope of this document. Airbus has rendered this issue moot to some extent by providing shared control as the A320's basic control mode. Pilot control inputs are considerably modified and shaped by the flight control computers; envelope limitations prevent him or her from exceeding pre-determined parameters. In this airplane, pilots are provided with considerable assistance even during control failure modes; manual flight capability is limited to rudder control and stabilizer trim and is designed only to maintain controlled flight while the automated systems are restored to operation. Under normal circumstances, the aircraft automation is responsible for much of the inner loop control, though control laws are tailored to respond in ways that seem natural to the pilot. In the MD-11, a combination of longitudinal stability augmentation and control wheel steering is in operation at all times; roll control wheel steering is available as an option.

When an autopilot is used to perform flight path (and/or power) control tasks, the pilot becomes a manager rather than a controller (this is also true to some extent of the shared control

option). The pilot may elect to have the autopilot perform only the most basic functions: pitch, roll and yaw control (this basic autoflight level is not available in all systems); he or she may direct the automation to maintain or alter heading, altitude or speed, or may direct the autopilot to capture and follow navigation paths, either horizontal or vertical. This is *management by delegation*, though at differing levels of management, from fairly immediate to fairly remote. In all cases, however, the aircraft is carrying out a set of tactical directions supplied by the pilot. It will not deviate from these directions unless it is incapable of executing them.

As always, there are exceptions to the generalizations. The A320 will not initiate a programmed descent from cruise altitude without an enabling action by the pilot. (This is the first instance of which we are aware in which management by consent has been embedded in aircraft automation.) Other modern flight management systems require that the pilots provide certain inputs before they will accept certain conditional instructions.

Management by consent implies a situation in which automation, once provided with goals to be achieved, operates autonomously, but requires consent from its manager before instituting successive phases of flight, or certain critical procedures. An example is given above. The consent principle has important potential advantages, in that it keeps pilots involved and aware of system intent, and provides them the opportunity to intervene if they believe the intended action is inappropriate at that point in time. (Taking the principle to its logical conclusion, it can be argued that even yaw damping in older airplanes is by consent, since the pilots can disable the function. This may not be the case in future aircraft, however, in which more of the automation will be transparent to the flight crew.)

This management mode may become more important as "smart" decision-aiding or decision-making systems come into use (see page 94). A protracted period of close monitoring of these systems will be necessary; requiring consent is one way to monitor and moderate the potential influence of these systems. While management by consent is an attractive option worthy of further exploration, it must be *informed* consent. More fundamental human factors research is needed to identify how to implement it without the consent becoming perfunctory.

Management by exception refers to a management-control situation in which the automation possesses the capability to perform all actions required for mission completion and performs them unless the pilot takes exception. Today's very capable flight management systems will conduct an entire mission in accordance with pre-programmed instructions unless a change in goals is provided to the flight management system and enabled by the pilots. This occurs relatively frequently when air traffic control requires a change in the previously-cleared flight path, most often during descent into a terminal area.

As previously stated, the desire to lighten the pilot's workload and decrease the required bandwidth of pilot involvement led to much of the control automation now installed in transport aircraft. The more capable control and management automation now in service has certainly achieved this objective, with benefits to safety, reliability and productivity. It also has the capacity, however, to decrease markedly the pilot's involvement with the flying task and even with the mission. Today's aircraft can be operated for long periods of time with very little pilot activity. Flight path control, navigation, and more recently subsystems management are almost entirely automatic. The capable, alert pilot will remain conversant with flight progress despite the low level of required activity, but even capable, motivated pilots get tired, lose their concentration and become diverted, or worry about personal problems unrelated to the flight. A critical task of the designer is to find ways to maintain pilot involvement during operation at higher levels of management.

This is less simple than it sounds, for pilots will both resent and find ways to bypass tasks that are imposed merely for the purpose of ascertaining that they are still present in the cockpit. Tasks to maintain involvement must be flight-relevant or even flight-critical, and equally important,

must be perceived by pilots to be relevant. Designing pilot involvement into highly automated systems will not be easy but must be accomplished to minimize boredom and complacency, particularly in very long range aircraft which spend many hours in overwater cruise. The progress of avionics, satellite navigation and communications, and data link may very well have an opposite result unless this uniquely human factor receives more consideration than it has to date.

(Today's aircraft are often easier to control than they are to manage, because interacting with flight management systems is accomplished primarily by entry of alphanumeric information. Reprogramming today's flight management computers can be cumbersome, and such flight path alterations are often more easily accomplished by reverting to a lower level of automation rather than by altering the FMS instructions. This in itself may be a problem, because some of the protection provided by the fully automated configuration may be removed by such reversion. On the other hand, reprogramming can occupy attention that might better be directed elsewhere. Making this interaction easier and less error-prone is a major task facing the human factors community, and a number of research efforts are underway to mitigate this problem.)

Autonomous operation denotes operation in accordance with instructions provided by system designers; no attention or management is required of the pilots. Until recently, relatively few complex systems operated autonomously. With the introduction of the A320 and MD-11, however, major systems operate in this way.

In the A320, the flight control system incorporates envelope limitation; this system operates at all times. Certain parameters (bank angle, pitch or angle of attack) cannot be exceeded by the pilot except by turning off portions of the flight control computer systems or flying below their cutoff values, as was done during the low-altitude flyover prior to the Mulhouse-Habsheim accident (ref. 44). Predetermined thrust parameters also cannot be exceeded. The MD-11 incorporates angle of attack protection, but its limits can be overridden by the pilot, as can the limits of the autothrust system. In the MD-11, aircraft systems also operate autonomously, to a considerable degree. Failure detection and subsystem reconfiguration are also autonomous if the aircraft system controllers (ASC) are enabled (the normal condition). Any system may be operated manually, though the protections provided by the ASC systems are not available during manual operation.

Systems designed for autonomous operation pose serious philosophical questions with respect to pilot authority as well as pilot involvement. These questions arose first in the design of fighter aircraft and were discussed succinctly in a recent unsigned editorial in *Flight International* (ref. 45). The American F-16 fighter's fly by wire control system incorporates "hard" limits which "preserve the aircraft's flying qualities right to the limit of its closely defined envelope" but do not permit the pilot to maneuver beyond those limits. The *Flight* editorial points out that "There is, however, another approach available: to develop a 'softer' fly-by-wire system which allows the aircraft to go to higher limits than before but with a progressive degradation of flying qualities as those higher limits are approached. It is this latter philosophy which has been adopted by the Soviets with fighters like the MiG-29 and Sukhoi Su-27. It is not, as Mikoyan's chief test pilot...admits, necessarily a philosophy which an air force will prefer." He says, however: "Although this...approach requires greater efforts...it guarantees a significant increase in the overall quality of the aircraft-pilot combination. This method also allows a pilot to use his intellect and initiative to their fullest extent" (ref. 46). The "softer" approach has been taken in the MD-11, which permits pilots to override automatic protection mechanisms by application of additional control forces.

Though civil aircraft do not face the threat posed to a fighter whose maneuverability is limited, they do on occasion have to take violent evasive action (see also page 86), and they may on extremely rare occasions need control or power authority up to (or even beyond) structural and engine limits to cope with very serious failures. The issue is whether the pilot, who is ultimately responsible for safe mission completion, should be permitted to operate to or even beyond airplane limits when he or she determines that a dire emergency requires such operation. The issue will not be simply resolved, and the rarity of such emergencies makes it difficult to obtain empirical support

for one or the other philosophy. Nonetheless, the issue is a fundamental one. Pilots must approach such limitations on their authority with extreme wariness; designers must recognize that hard limits place them, rather than pilots, in the position of ultimate command, given the capability and flexibility of automated systems. Pilots must also be concerned about the effects such systems may have on their perception of their responsibilities, which remain despite whatever protective systems may be installed. Such systems can fail.

Another fundamental question is how wide a range of control and management options should be provided. This may well vary across functions; indeed, pilots will often operate at a range of levels, for example controlling thrust manually while managing the autopilot and using the flight director to monitor navigation. Pilot cognitive styles vary; their skill levels also vary somewhat as a function of the amount of recent flying they have done, how tired they are, etc. These factors lead us to argue that a reasonable range of options must be provided, but widening the range is expensive in terms of equipment costs as well as of training time and time required to maintain familiarity with a broad spectrum of automation capabilities.

One way to keep pilots involved in the operation of the aircraft is to limit their ability to withdraw from it by invoking very high levels of management. Another, perhaps preferable way is to structure those higher levels of management so that they still require planning, decision-making and procedural tasks. The use of a management by consent approach, rather than management by exception, could be structured to insure that pilots must enable each successive flight phase or aircraft change of status, as an instance. It has been suggested by one air carrier that long-haul pilots should be given the tools with which to become involved in flight planning for maximum economy on an ongoing basis; this is another approach to maintaining higher levels of involvement.

Control Automation in the Future

Control automation is already highly advanced and highly competent. What may we reasonably expect to see in the way of further advances? What additional factors should be considered in this domain?

There is increasing concern regarding the problem of runway incursions, as airports become more and more congested. Several studies (refs. 47 and 48) have highlighted this problem; two recent accidents, at Detroit and Los Angeles, have underscored its seriousness (ref. 84). Improved radar surveillance of airport surfaces is technically feasible and new devices are scheduled for installation; light systems at runway-taxiway intersections have been tried in the United States and are in use elsewhere, but neither of these approaches will be fully effective in mitigating the problem of human (either pilot or controller) error (ref. 49).

More error-resistant and error-tolerant approaches to this problem are needed, especially given problems of low visibility and contaminated taxiway surfaces which can obscure markings temporarily. Suggested approaches include some degree of automation in control and conduct of movements on the airport surface. Automation has not been extended to control of aircraft on the airport, though techniques for lane-holding have been attempted in automobiles on roadways with embedded wiring. Highly precise satellite navigational aids, particularly when accuracy is enhanced by fixed-installation comparison techniques such as differential GPS (ref. 50), may provide the means for true all-weather control of airplane positions on the ground. If airport features can be described precisely, automatic control of aircraft during taxi is possible, though it will require very large databases in the flight management systems that will access the information and very accurate map displays in the cockpit.

It needs to be pointed out that if automated control of aircraft on the airport surface becomes a reality, pilots will be unable to verify the correct operation of the automation under conditions of severely limited visibility. Before such technology is implemented, it will be necessary to consider

how an independent monitoring capability can be provided. One possibility may be the use of millimeter-wave radar and the provision of synthetic visual display devices in the cockpit (such systems could also provide independent monitoring capability during low-visibility approaches, and with the addition of other information to the displays, might provide independent takeoff monitoring capability as well).

Although today's aircraft have the capability to follow an ILS localizer centerline accurately and this capability is made use of during automatic landings, automatic takeoffs using centerline guidance are not performed, probably because of concern about asymmetric power failures and the ability of autopilots with limited authority to maintain directional control during an aborted takeoff. Certainly the pilot is more quickly able to counter variations in direction if he or she is involved in inner-loop control, but during extremely bad visibility the pilot also introduces perceptual delays in detecting deviations from centerline.

Microwave landing systems are in an advanced state of development; they permit the conduct of more complex curved approaches and may thereby increase runway acceptance rates while mitigating some noise problems for communities in the vicinity of airports (ref. 51). Flying very complex approaches will lead to appreciable increases in flight crew workload, however, even if the approaches are automatic. Alternate means are being explored to enable equivalent approaches using existing equipment capabilities, but these too will involve higher cockpit workload. The expected gains are great enough so that such approaches will probably be required in the future system.

We may certainly expect to see more highly integrated automation suites in virtually all future transport aircraft. A higher level of integration may permit simpler automation architectures that are more easily and intuitively understood by pilots, though the trend to date has been toward greater perceived complexity. Whether the range of options available to the pilot should be narrowed is an open question. Even before the advent of the present generation of aircraft, incidents were reported in which pilots became confused about the mode in which they were operating; this led to a stall at high altitude in the case of an Aeromexico DC-10 departing Frankfurt (ref. 12); the elevators sustained severe damage during the recovery process, though the airplane was flown on to its destination.

It should be pointed out again that problems such as this may be due to the automation of a control function which should not have been automated, but they may equally well be due to failure to make a needed function sufficiently obvious, that is to poor implementation of an appropriate function for automation. Our first principles state that the pilot must be involved; they also state that the pilot must be informed, and this includes prominently being informed, *at the level required for him to fulfill his responsibilities*, of the airplane and automation characteristics at all times. As is pointed out several times here, too much information may be as bad as too little, the critical point is that the pilot must be able to maintain state and situation awareness.

As subsystem automation becomes more capable and more common, we shall have to consider carefully what subsystem management actions should *not* be automated. In the MD-11, Douglas has refrained from automating fully any tasks that are irreversible in terms of their effect on the airplane's ability to complete its mission. In future aircraft, we must consider as well whether certain actions that can be taken by pilots rather than by the automation should also be proscribed, or at least made to require confirmation or consent. There have been two cases in which pilots shut off fuel to both engines of a twin-engine transport shortly after takeoff, thinking that they were operating its electronic engine controllers (ref. 52). In these cases, either designers did not recognize the potential for the specification of procedures that could be hazardous, or the air carriers did not understand the (designer's) intent for the EEC enable/disable function, or both. Designers and purchasers of aircraft, and pilots as well, must understand automation intent equally if the potential for error is to be minimized.

Our first principles suggest that the automation must be able to monitor the pilots. Monitoring automation could certainly be designed to question certain classes of pilot actions that can potentially compromise mission completion, though for the automation to proscribe such actions would again limit the authority of the pilot. It is hoped that more serious thought will be given to the pilot-automation and automation-pilot monitoring functions, both of which are enabled by the highly competent digital computers now in place in advanced aircraft.

Information Automation

We next examine what Fadden has termed *information automation*. Though primitive levels of information automation have been present for some time, information automation began its explosive growth with the introduction of the "glass cockpit," in which CRT screens replaced some or all of the older electromechanical instruments. Even prior to this development, information management had become a major problem in aviation. Billings, Lauber and Cooper cited information management as one of the principal issues in an informal interview study with flight crew of a U.S. flag carrier in 1974 (ref. 53). An early ASRS study found information transfer problems in 73% of 12,000 consecutive incident reports (ref. 54).

The advent of CRT screens in cockpits made it possible for designers both to provide more visual information and to provide it in flexible formats. At a time when more and more information was becoming available, the temptation was very great to provide pilots with much more information than had previously been supplied. Further, pilots were not hesitant to demand more information than they had before; experimental studies have found that pilots want as much information as may possibly be relevant, even at the cost of increased workload (ref. 55).

Though pronounced differences in philosophy exist among the major suppliers of transport aircraft, most have been fairly conservative about new cockpit displays. It should be recognized that automation, which enables more information to be presented, also carries with it costs in terms of the amount of information required to monitor the automated functions, as shown in figure 16.

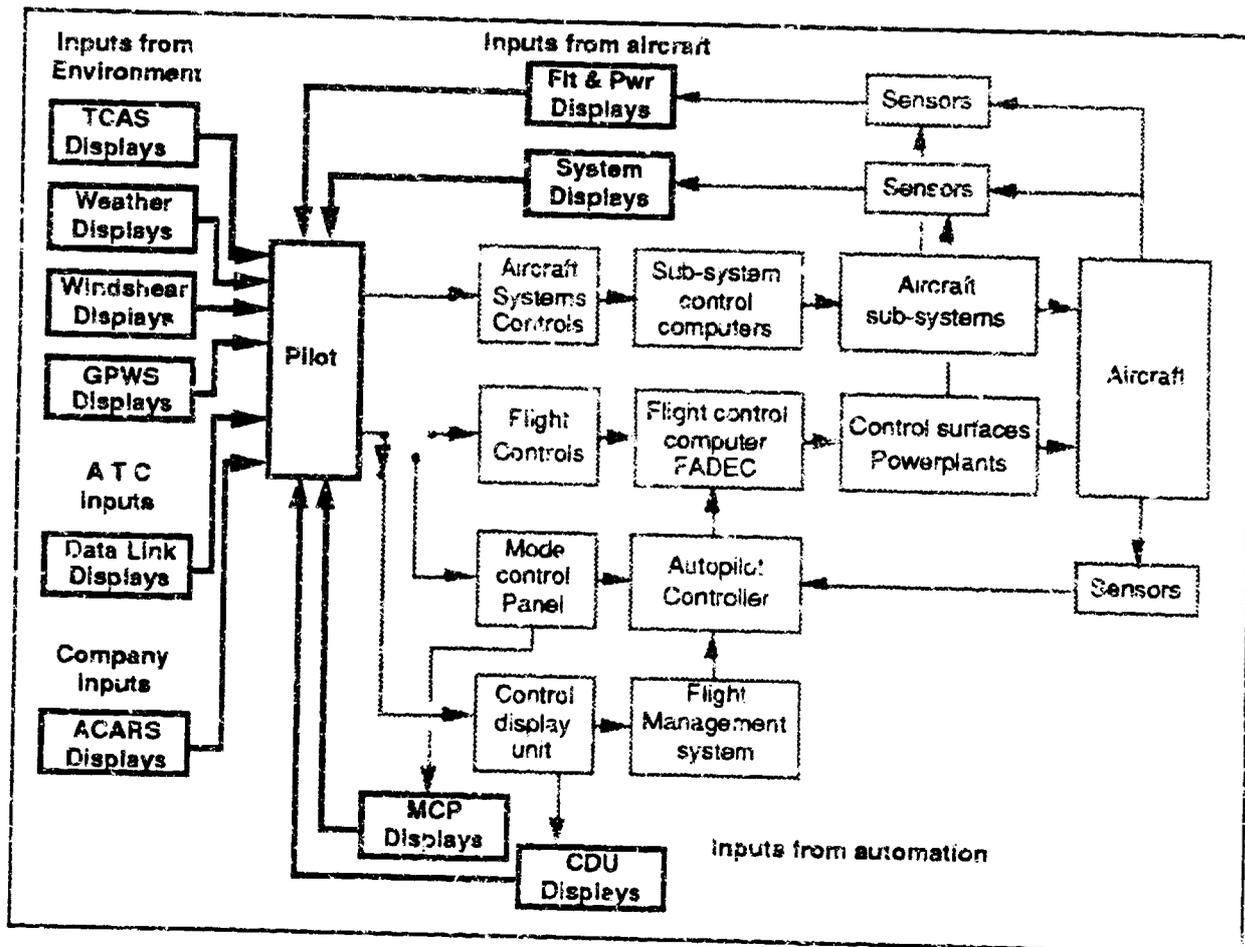


Figure 16: Information automation

Despite this conservatism, new alerting systems have been introduced, several mandated by Congressional decree; each requires the presentation of new information to pilots. Ground proximity warning systems, mandated in 1974, provide visual and aural warnings. Traffic alert and collision avoidance systems (TCAS), now being installed in all transport aircraft, provide visual displays and visual and voice warnings of traffic threats. Windshear advisory systems, mandated for installation during 1991-1993, will also introduce visual and aural warnings.

Though map displays have greatly simplified the presentation of navigational information, the integration of weather radar data and TCAS traffic displays with navigational data has complicated those displays considerably, especially on smaller CRTs. The coming of digital data link for ATC messages will add still further visual displays that must be attended to. We will now examine the kinds of information in the cockpit, the ways in which it is displayed, and the effects of automation on the information provided to flight crews to enable mission accomplishment.

Flight path displays: Pilots are physiologically unable to maintain a stable airplane attitude by reference only to their own sensory inputs because of limitations in their ability to sense motion and acceleration in all spatial axes (ref. 56). The first attempts by Doolittle and others to develop systems for instrument flight (ref. 57) were prompted by the recognition of this fact. Gyroscopic turn indicators and ball slip indicators provided data concerning turn rate and sideslip; airspeed and altitude indicators provided coarse information concerning climbs and descents. Two-axis gyroscopes provided sensing for the more intuitive artificial horizon, which accurately displayed bank and pitch angle on a single device; another single-axis gyroscope provided heading information when set in accordance with a magnetic compass. Vertical speed instruments were added to show rate of change of barometric altitude (figure 17).

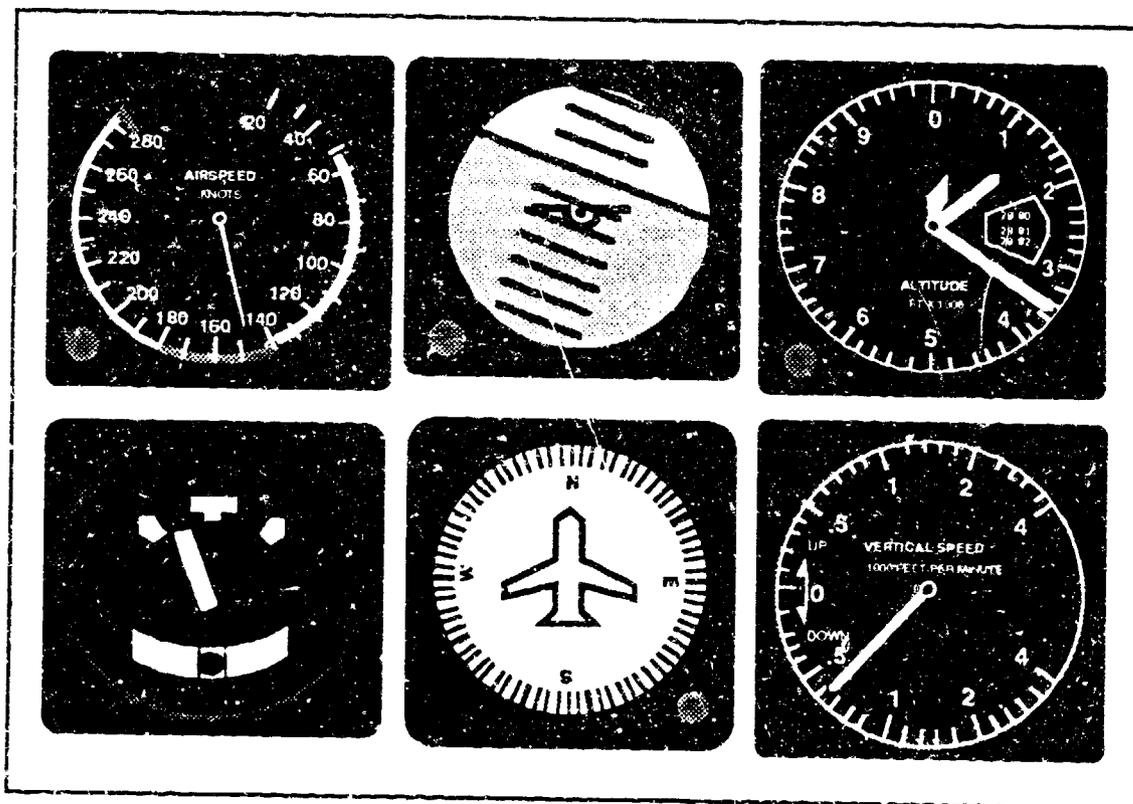


Figure 17: Primary flight instruments: airspeed indicator, artificial horizon, three-pointer altimeter, turn and bank indicator, directional gyro, vertical speed indicator. The airplane is in a left turn, without sideslip, at 147 knots, descending from 1340 feet at 630 feet per minute.

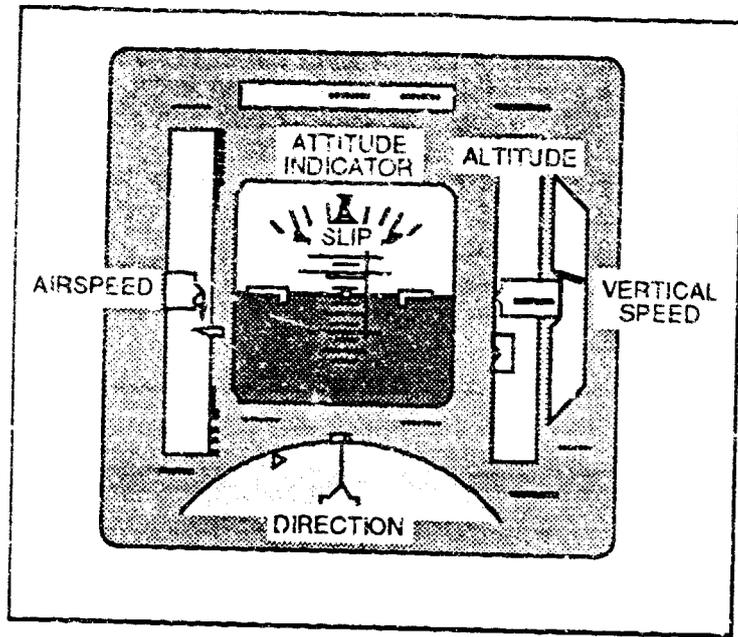


Figure 18: Electronic primary flight display.

The information provided by these six instruments has been the foundation of instrument flying ever since. Analogous information, though derived in many cases from different sensors (air data computers and inertial reference platforms), is still the basis of the primary flight display in the newest and most sophisticated aircraft (figure 18). The several sources of data, in different formats, require considerable mental integration to permit the formation of a coherent perception of the airplane's attitude, state, and rate of change. In advanced electronic displays, a variety of aids is made available to assist the pilot in maintaining this perception, but the basic information displayed is not fundamentally different.

Over the years, human factors researchers and design engineers have brought forth a variety of concepts for the simplification and integration of the information presented in the primary flight displays. Most of these have involved some sort of "pathway through the sky" concept (fig. 19). Such a display, devised by Grunwald and colleagues, has been tested in simulation and flight, and is still under development (ref. 58). Air Force human factors experts have likewise looked for simpler means by which to convey primary flight information (ref. 59). Airframe manufacturers have shown interest in such concepts, but have been inhibited in bringing them to service use by the mix of aircraft in nearly all fleets. Pilots fly a variety of aircraft during their careers, some with advanced cockpits, some with conventional electromechanical instruments. There has been considerable concern that transitioning back and forth between the older displays and advanced, more integrated, displays could increase training requirements and perhaps compromise safety.

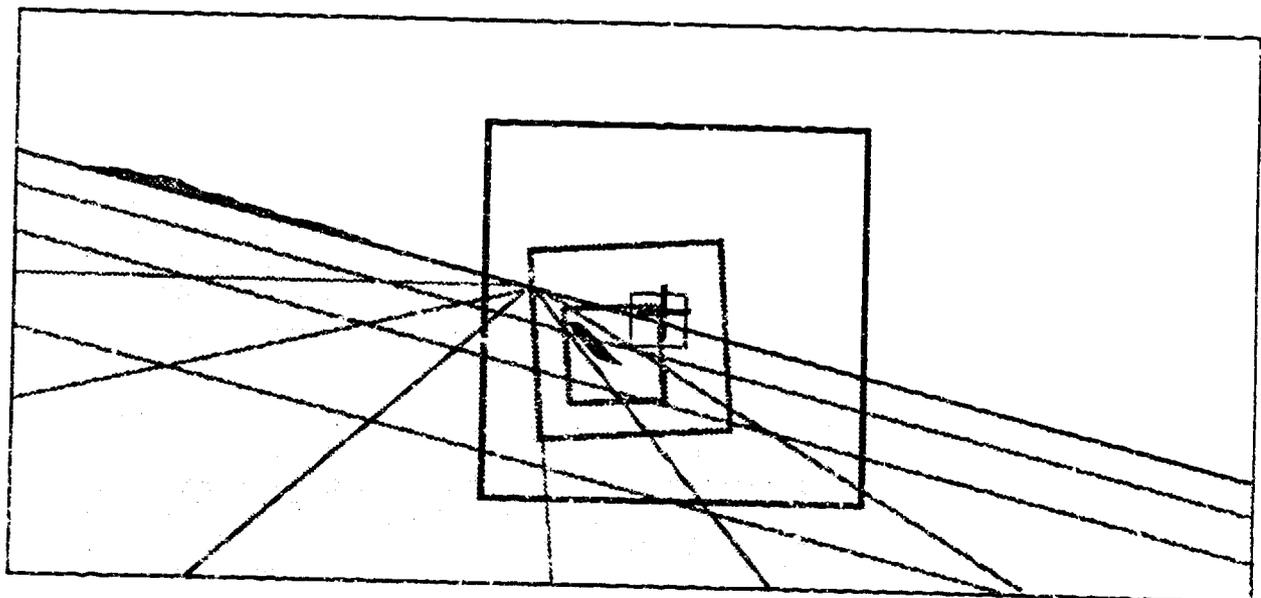


Figure 19: Pathway in the sky display.

In older aircraft, several displays are also used to provide navigational (more properly, position) information to pilots. In essence, pilots are informed of their bearing and distance from a radio navigation aid, or during inertial flight, from a geographic waypoint defined in the flight management computer. During approaches, they are informed of their lateral and vertical deviations from localizer and glide slope centerlines. This information, like attitude information, must be considerably transformed to permit the derivation of present position. Figure 20 is a sketch of this information. It shows a horizontal situation display containing a heading indicator (whose data now comes from a remotely-mounted, stabilized magnetic compass), a digital display of DME distance, and a radio magnetic indicator (RMI), showing the bearing to two VOR stations (whose data now comes from a remotely-mounted, stabilized magnetic compass), a digital display of DME distance, and a radio magnetic indicator (RMI), showing the bearing to two VOR stations or low-frequency radio beacons. The RMI also contains a heading indicator, whose inputs are normally from a second independent magnetic compass unit.

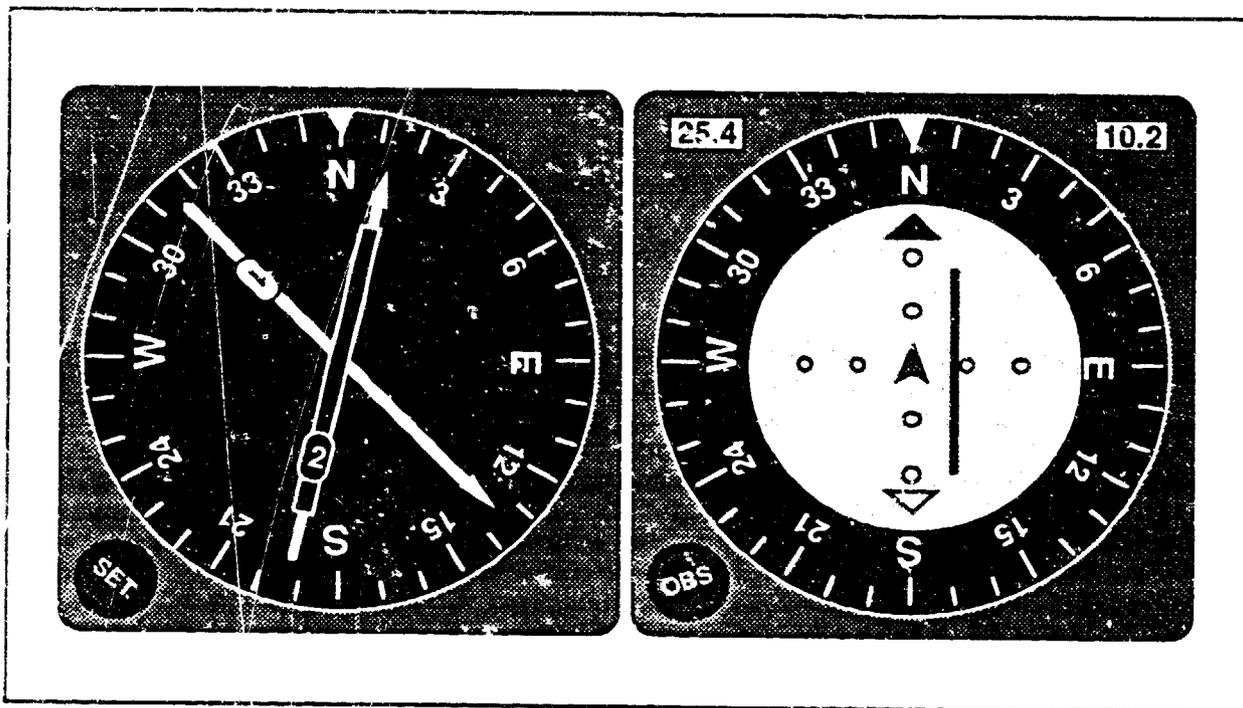


Figure 20: Electromechanical navigation instruments: radio magnetic indicator (RMI) to left, horizontal situation display (HSI) to right. The 180° radial of the VOR being tracked is 12° to the right; the VOR is 10.2 miles away. Aircraft is flying parallel to that radial. The HSI also shows glide slope deviations when tuned to an ILS frequency.

The introduction of CRT screens in the cockpit made possible drastically simplified navigation displays. Although conventional HSI displays like that shown above are still provided, nearly all pilots of glass cockpit airplanes use map displays for most enroute flying. The map displays utilize data stored in the flight management system to provide a pictorial platform display of present position and future navigation waypoints. In some aircraft, terrain obstructions and airports can also be selected. In most glass cockpit aircraft, weather can also be depicted on the display; displays of other traffic are, or will be, provided by TCAS equipment.

When all of these options are exercised at once, screens can be cluttered if significant weather or a great deal of nearby traffic is present, but the displays still require less mental effort on the part of the pilot. Many navigation displays can also be used in a "north-up mode" to display the route programmed in the FMS computers. The scale of the navigation display can be varied; some TCAS units also permit altitude filtering. Figure 21 shows such a navigation display. It includes flight plan, present and predicted flight path, waypoint and radio navigation aid locations, location of weather, altitude relative to planned altitude, inertial ground speed and wind direction and speed.

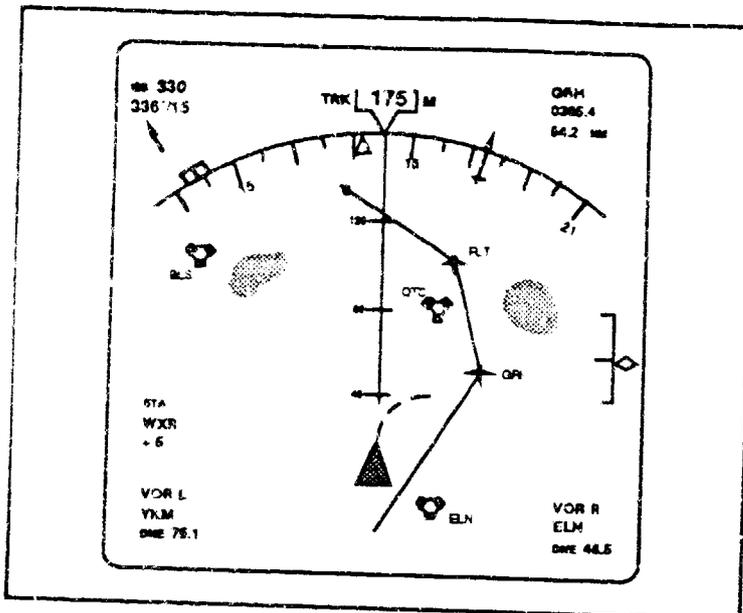


Figure 21: Electronic map display showing weather, flight plan route and nav aids.

Map displays have immeasurably eased the cognitive tasks of pilots by giving them an instantaneous, easily-interpreted picture of their location with respect to their plan. Wiener (1989) reported that they are the most desired single feature of advanced automation. As with flight directors, it is not difficult to lose sight of the raw navigation data. Map displays do not make it particularly easy to evaluate the raw data from which position is derived, and it has been necessary to introduce special display elements to aid in this task. American and British incident reports (ref. 60) describe circumstances in which the apparent position was incorrect, and the clarity and apparent precision of the displays can be seductive.

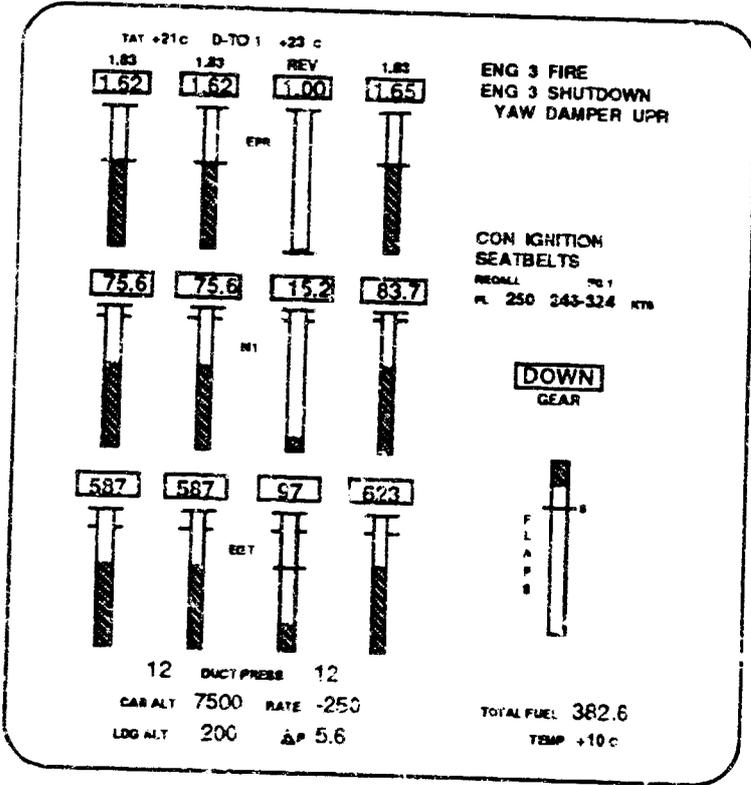


Figure 22: Primary EICAS display, Boeing 747-400.

Power displays: The Boeing 757/767 introduced electronic engine status displays. These displays provided enhanced electronic depictions of information that had been available on electromechanical instruments, together with adaptive EGT limits, data on commanded vs. actual thrust for autothrust operation, etc. The later Airbus A320 provided a similar set of electronic displays and alphanumeric information. The Boeing 747-400 electronic power displays were the first to utilize a simplified tape format on a primary and secondary display (figure 22). A compacted format showing analog tape and alphanumeric data is also available. These displays were based on research showing that pilots were better able to evaluate engine problems with displays tailored to the number of engines. The MD-11 primary and secondary power displays are again CRT representations of the earlier electromechanical displays.

It is interesting, in view of the integration of information in glass cockpit navigation displays, that more integration and processing of engine and power information has not been utilized in current-technology aircraft. Abbott and coworkers at Langley Research Center have proposed a

concept for a considerably-simplified set of power displays using bar graphs which show relative data vs. appropriate values for engine parameters (ref. 61). (See page 44 for discussion.) The engine monitoring and control system (E-MACS) concept will be evaluated in flight simulations as a part of the NASA Aviation Safety/Automation concept demonstrations.

Configuration displays and alerting systems: In older aircraft, a variety of lights and gages were used to show the configuration of landing gear, flaps and slats, control surfaces, aircraft doors and other flight-critical systems. Nearly all current-generation aircraft have displays that provide such information in graphic form, though Airbus Industrie has gone farther than other manufacturers in showing the configuration of components of these systems as well as the systems as a whole.

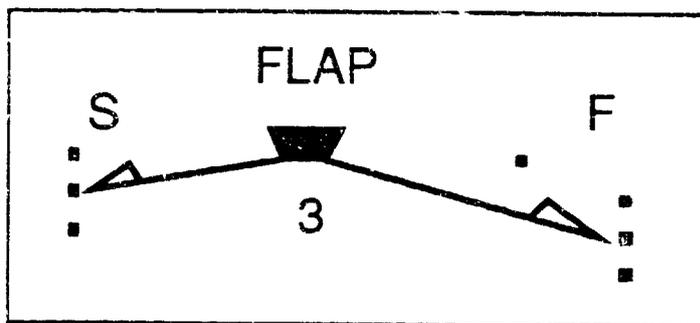


Figure 23: Electronic display of flap-slat positions in A320.

Figure 23 shows an elegant little icon used in the A320 to indicate flap and slat position. The diagram appears on the engine display screen together with engine data, status and alerting messages. The number refers to flap selector position.

Alerting messages and aural signals are still used in newer aircraft for critical items prior to takeoff and approaching landing, as in earlier generations. These takeoff and land-

ing configuration warning systems have prevented many accidents, but their occasional failure, and their ability to generate spurious or nuisance warnings, raise a problem of a more general nature. Devices that are extremely reliable will come, over time, to be relied upon by pilots. In the rare cases when they fail, or are disabled, pilots may not be sufficiently alert to detect the condition for which the device was originally provided. This occurred in two recent attempted takeoffs with flaps and leading-edge devices retracted. The aircraft crashed with heavy loss of life (refs. 10,11).

The other side of this coin is that devices that produce too many "false alarms" will be mistrusted by flight crews. In the extreme case, they will simply be ignored after pilots have become accustomed to them. This was the case when the earliest model of the ground proximity warning system (GPWS) was introduced. At least two accidents have occurred because pilots ignored, disabled or were slow to respond to warnings that were appropriate. Later GPWS models incorporated more complex algorithms and the number of nuisance warnings dropped dramatically. We are now seeing similar problems with large-scale implementation of TCAS-II.

Altitude alerting systems, introduced to alert pilots when approaching a selected altitude and to warn them if they thereafter depart from that altitude, provided both aural and visual alerts many times in the course of routine flights. They were reliable and came to be depended upon; altitude excursions resulted when the devices malfunctioned or were ignored because of distractions. Pilots objected, however, to the number of aural alerts approaching altitude, and FAA amended its requirements to permit the use of only a visual signal approaching altitude. After this change was made, pilots accustomed to hearing the aural alert before reaching their selected altitude were also involved in altitude excursions because it was no longer present (ref. 62).

Color is used in all cockpits to indicate problems (red or amber, depending on severity), though display symbology and color-coding for CRT displays has not yet been standardized. The Society of Automotive Engineers S-7 Committee is working on such a recommended standard. In most cases, redundant shape or size coding is used in addition to color, to minimize detection problems for color-deficient pilots and to maximize legibility in bright sunlight (though CRTs used in cockpits undergo stringent testing to insure readability in very bright light).

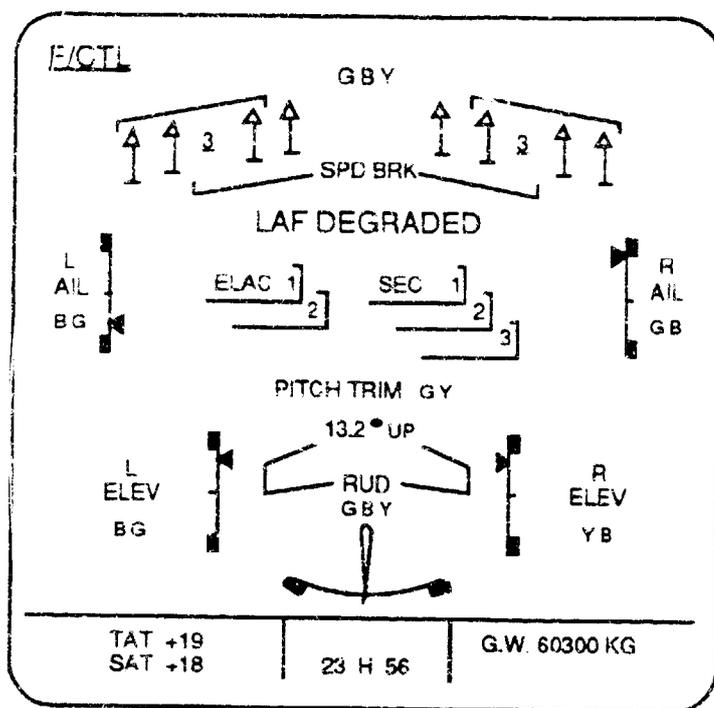


Figure 24: Flight control configuration display, A320.

The complexity of configuration displays can be high because of the number of items that are pertinent (figure 24). Though color can help to direct a pilot's attention to parameters that are abnormal, a good deal of information must still be scanned. Cockpit designers have done an excellent job of eliminating large numbers of discrete "lights, bells and whistles," within limits imposed by certification regulations, but they have substituted large amounts of discrete data integrated into a smaller number of displays.

This topic is discussed in more detail in following sections, but it should be said here that current operational constraints often require pilots to review, by whatever means, a great deal of important status information prior to takeoff and during approach, periods that are already busy. Ways of summarizing this information that can alert pilots if

a potential problem is present are highly desirable, but only if they are trustworthy, for pilots will come to depend on such aids. "Automation must be predictable," but it must also warn unmistakably when it is unable to perform a flight-critical function.

Subsystem displays: Though there is still a philosophical controversy about the necessity or even the desirability of providing synoptic subsystem information in the cockpit, pilots and operators clearly find it desirable to have such displays and they are provided in most glass cockpit aircraft. Synoptics of simple systems may increase the risk of misinterpretation, though they are probably advantageous for the depiction of more complex systems. Some of the controversy probably relates to certification issues; manufacturers and operators alike wish to incorporate as few essential systems as possible to avoid grounding airplanes when they fail, and the overhead panels on these aircraft permit full manual operation of all subsystems.

Like configuration displays, subsystem synoptic displays can be very complex, though most manufacturers have made them as simple as possible. Multiple faults, however, will still require careful pilot attention to the screens to understand fully the nature of the problems. Herein lies another facet of the controversy. Modern airplanes are designed to require specific actions (usually as few as possible) in response to any fault or combination of them. The required actions are spelled out in checklists which are designed to be followed precisely. These aircraft are also designed to require no more than checklist adherence for safe flight completion. There is continuing concern among designers that providing too detailed information on subsystem configuration may lead some pilots to adopt more innovative approaches to complex problems, and thereby negate the care the manufacturer has taken to simplify fault rectification. Such behavior has caused serious incidents in the past and will probably continue to do so in the future despite the best efforts of designers to achieve simplicity and clarity in their designs and procedures.

On the other hand, pilots argue, with justification based on experience, that faults not contemplated by the manufacturer may well occur in line operations. They point, as one instance, to a L1011 that was landed safely at Los Angeles after its crew was faced with a completely

unanticipated control surface fault for which no book solution existed (ref. 63). They do not wish to be deprived of any information that could assist them in coping with such problems.

The Boeing 757/767 cockpit, as indicated above, does not provide subsystem synoptics, though EICAS messages provide a great deal of information on aircraft system status. Since not all information can be presented, the questions that must be answered is at what point the appropriate compromise can be found. Better models both of system behavior and of cognitive responses to malfunction information are needed to answer this question. Such research is underway within the NASA Aviation Safety/Automation program (ref. 64).

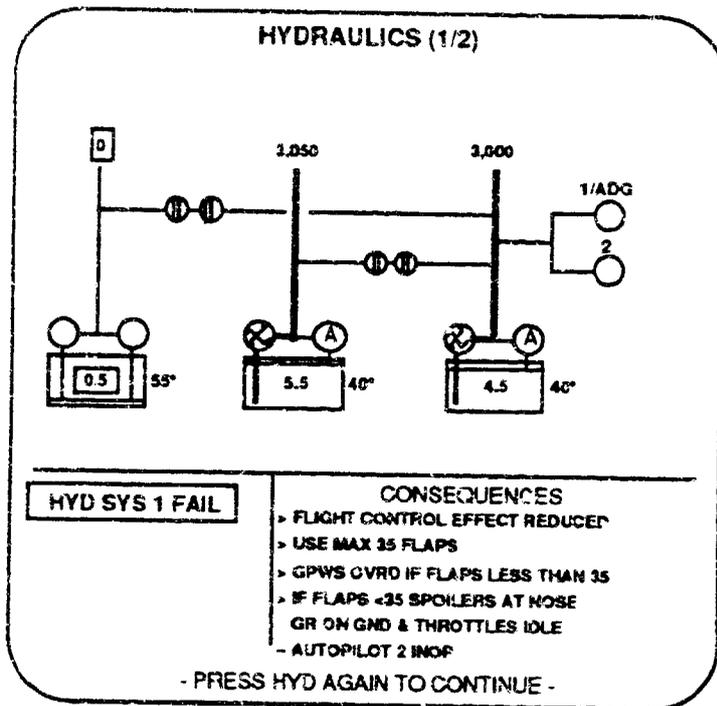


Figure 25: Hydraulic system synoptic page, MD-11.

As noted above, Douglas Aircraft has taken a different approach to subsystem management in that it has automated most normal and abnormal actions in the MD-11 subsystems. The synoptics in the MD-11 are simplified diagrams of each subsystem. When an abnormal condition is detected, the appropriate system controller takes action; an alerting message is displayed on the engine and alert display. The appropriate subsystem pushbutton on the systems control panel is also lighted. When actuated, this pushbutton brings up the synoptic, which will show the system diagram with altered icons indicating the fault, what action has been taken, and a list of the consequences for the conduct of the remainder of the flight. Figure 25 shows an example of a level 2 alert (system A hydraulic fluid loss) which has been resolved automatically by inactivation of the two system A hydraulic pumps (system at left of the

synoptic diagram) after low system A hydraulic quantity was detected. The depleted system A hydraulic fluid reservoir is also shown.

Here, the synoptic display is very clear (and compelling); there is no question about what has failed and what has been done about it, although a failed sensor could produce the same display as a failed system and the pilot must still differentiate between these two conditions. This leads to a question about whether such systems should be permitted to be reconfigured autonomously, without pilot consent. The designer of such a system bears the heavy burden of insuring that the action taken by the automation is always appropriate and that it will not under any circumstances worsen the situation. Ascertaining this may be comparatively simple for many faults; for others, it may not be. The design philosophy appears to have been effective in lightening pilot workload; more experience will be necessary to determine whether it has unwanted effects as well, aside from the minimal burden of monitoring the automation. Alerting messages appear if any of the automatic aircraft system controllers fail; the computers reconfigure the subsystem for manual operation if both of the dual channels become inoperative.

It must be kept in mind that sensors, processing equipment or display generators can fail, and that when incorrect information is presented, or correct information is not presented, there is the

potential for confusion in the minds of the pilots. This adds complexity but must be accommodated. The information must be important enough to warrant the added complexity.

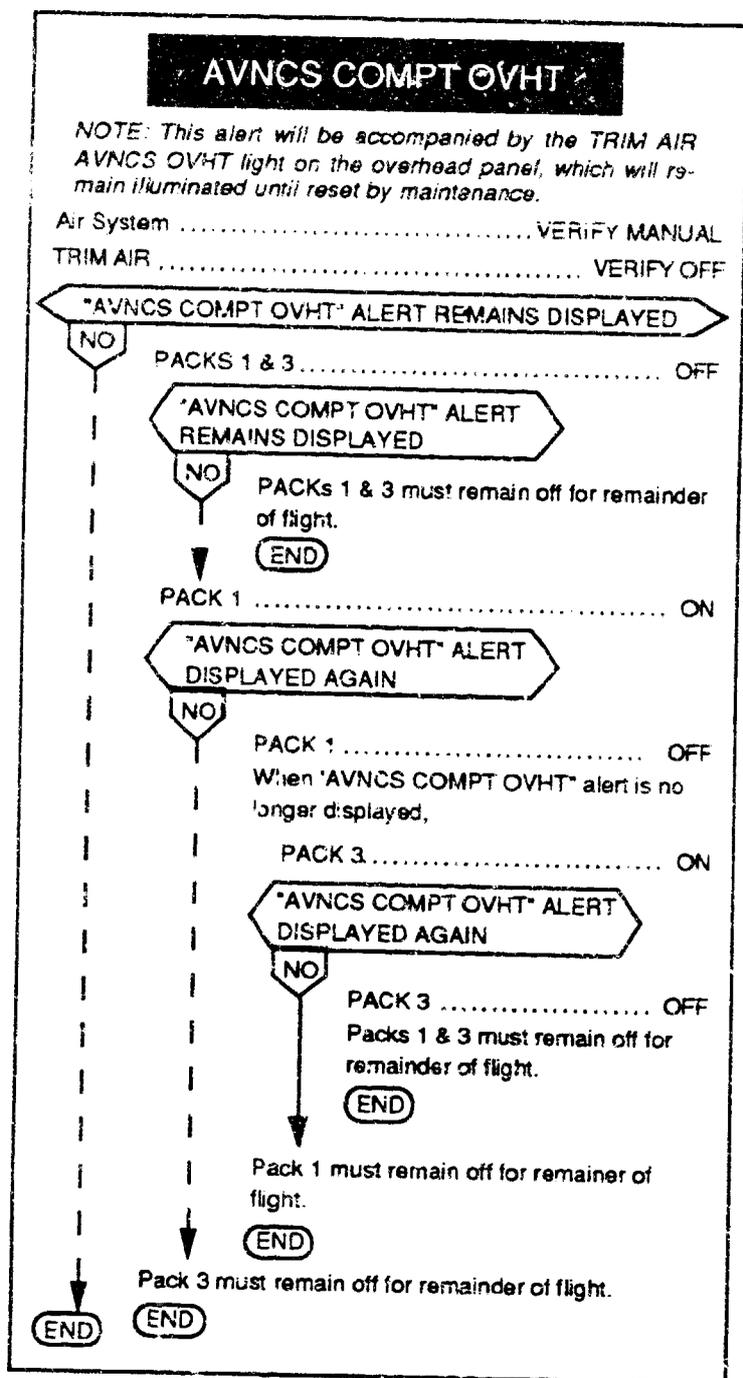


Figure 26: Quick Reference Handbook checklist, MD-11.

Information displays: Many new information displays have been enabled by flight management computers and CRT display media. At the upper left corner of figure 21, a box shows ground speed, wind direction and velocity, and an arrow also shows wind direction relative to the airplane's track. This information was previously available on the FMS alphanumeric screen, but the arrow provides the information in a more immediately understandable form. In the same diagram, a curved predictor display shows where the airplane will be at some time in the

It has been suggested here that though many subsystem displays, and some systems, have been considerably simplified, other subsystems have become more complex. Older aircraft contained several hundred discrete cockpit alerting and warning signals (ref. 65). In current-technology aircraft, a small area on the primary EICAS or ECAM screen is considered adequate for the presentation of all warning and alerting messages (though scrolling through such messages may be necessary with compound faults). The messages themselves are highly abbreviated; quick-reference handbook checklists contain procedures for each abbreviated alerting message.

While the number of discrete alerting devices has decreased markedly, the number of discrete alerting messages that may be displayed and may require action is still large, though the number of level 3 (emergency) warnings has been kept as small as possible and non-essential warnings and alerts are inhibited during takeoff and final approach. Nonetheless, fault management may still be complex, and newer aircraft are operated by a crew of two instead of the former three persons, so there may be more for each crew member to do. It is largely for this reason that Douglas has automated many MD-11 subsystems management tasks. A sample QRH page is shown in figure 26. It contains the checklist to be followed in the event of an avionics compartment overheat alert. A manual troubleshooting procedure is diagrammed logically.

future if it continues in its present turn. In figure 18, a small arrow pointing downward from present airspeed is a trend vector; it points to the airspeed of the airplane 10 seconds hence if its present rate of deceleration continues. These are just a few of a large number of enhanced information displays made possible by automated systems in glass cockpit aircraft.

A good example of enhanced information displays is the use of the navigation display for flight plan verification. The entry of geographic waypoints into the FMS prior to departure is known to be an error-prone task; elaborate procedures involving the entire flight crew have been instituted to decrease the likelihood of errors in performing this task. Nonetheless, input errors do occur, are not obvious, and can be extremely serious. The destruction of a Korean Air Lines 747 over Soviet airspace is thought to have been due in part to an INS programming error that occurred many hours earlier, before takeoff from Anchorage (ref. 66). In a more recent case, a Delta 747 and a Continental DC-10 nearly collided over the Atlantic due to an input error by the Delta crew before takeoff (ref. 67).

Newer automation permits the use of the navigation display for graphic visualization of flight plans. An expanded range (up to 640 NM in the 747-400 and MD-11), north-up presentation of the flight plan enables the flight crew to detect obvious or gross errors in the waypoints they have inserted into the FMS. At present, no terrain or other geographic orienting features are contained in FMS databases, but it is expected that future electronic library systems (see below) will contain such features; they can be used to provide even more assistance to the crew in detecting errors in flight plan construction. As always, there will be the added cost of learning to manage the new system and of still more information availability.

Even older aircraft incorporate a variety of more-or-less automated information displays; the altitude alert system discussed on page 38 is an example. A manually-set digital altitude reminder is compared with actual barometric altitude; alerting signals indicate when the airplane approaches, attains or later departs from the selected altitude.

Aircraft equipped with flight management systems but electromechanical instruments utilize a small monochromatic CRT display in the FMS CDU for the presentation of alphanumeric information derived from the FMS. These screens will undoubtedly also be used for digital data received by data link units in such aircraft. TCAS incorporates a planform display of traffic in the vicinity of one's own aircraft. In some installations a dedicated CRT is used; in others, TCAS information may be shown on a color radar screen, while in others, a new color display combines a presentation of the instantaneous vertical speed indicator (IVSI) with a small planform display of traffic. This instrument replaces the conventional IVSI. In nearly all glass cockpit aircraft, it is expected that the information will be shown on navigation and flight displays.

Discussion of Information Automation

The purpose of information automation in the cockpit is to enhance the flow of information to the flight crew. This information is necessary to permit the crew members to maintain full awareness of their situation. "Situation awareness" is a term in wide use, but it has been difficult to define at all precisely. It is thought that much of the difficulty in arriving at an acceptable definition may be semantic rather than substantive; like other terms of art, it may be more difficult to define than to understand. Sarter and Woods have reviewed the literature and have suggested ways of delimiting the term more effectively (ref. 24).

In situation awareness, we include the crew's perception of the state and status of their airplane, its position in space, and the state of the physical and operational environment in which it is operating and will operate in the immediate future. Information automation, like all other aircraft automation, must assist the crew in maintaining situation awareness.

Flight path displays: Given the integration of information that has taken place in newer cockpits, it may seem strange that alternative, more integrated primary flight displays have not yet appeared in transport aircraft. In fact, the primary flight display (PFD) shown in figure 18 does represent a step forward, in that the information previously shown on five or six instruments has been combined on one screen, carefully designed to promote rapid scan of its elements. There is much controversy with respect to the optimal layout of this screen, whether the airspeed tape should have higher numbers above or below, how much information should be shown in various phases of flight, etc., but almost none among operators and manufacturers about whether the basic format should be retained.

The flexibility of CRTs has made it possible to present much more information on a single PFD than was available in one place in electromechanical cockpit displays. The airspeed indications, in particular, have been increased. Pilots were formerly required to set "bugs" (small manual pointers on the circumference of the airspeed indicator) as reminders of critical speeds; in current aircraft, these are presented automatically on the airspeed tape, and may be stored in the FMS database. Whether having to look up and set these speeds manually in older aircraft improved pilot awareness of them, and whether anything has been lost by providing them automatically, is not known. Pilot errors in setting them have certainly been reduced.

Trend information based on acceleration or deceleration may also be available, as are not-to-exceed and minimum safe speeds based on weight and airplane configuration. Bank and pitch limits for maximum performance are shown on the attitude indicator. Pre-selected altitude or decision height limits, indications that key altitudes are being approached or have been exceeded, and altitude trends may also be shown (although the IVSI, located at the extreme right of the PFD, also provides rate of change information). TCAS resolution advisory information requiring a climb or descent to avoid conflicting traffic is also shown on the IVSI and is reinforced by voice warnings. Windshear advisory information will also be shown on the PFD and will also be accompanied by voice warnings.

Can all of this additional information be assimilated by the flying pilot? Experience to date would suggest that it can be. Has anything important been lost in the compression of a large quantity of information onto the surface of a single display? There are indications (Fadden, personal communication) that at least some pilots experience more difficulty in maintaining airspeed and altitude precisely when the relevant information is displayed in a tape rather than round-dial format. This may be due to sub-optimal design of the tape displays, though efforts to improve the displays do not appear to have resolved the problem entirely. The phenomenon is not known to have caused significant difficulties in line operations, though no specific research has been conducted to determine this. There have been cases in new-technology aircraft in which airspeed (presented in tape format) has decayed to dangerously low levels during approaches to landing, but it is not possible to determine whether this was due to the display itself or to over-reliance on other protective features of the automation which were not, in fact, operative in the mode being used.

Despite the apparent effectiveness of CRT primary flight displays, human factors researchers continue to explore alternative formats involving a more path-oriented display of attitude, position, state, and future path. The limited research that has been conducted indicates that such displays can be an effective substitute for the conventional PFD under the conditions studied, but whether there are conditions under which such displays would *not* provide sufficient information is not known, and it is also not known whether such innovative displays would convey significant improvements in safety over the conventional displays. In the absence of data on these points, and given the questions raised earlier about transition between glass and electromechanical cockpits (page 35), manufacturers and operators have elected thus far to remain with conventional displays.

Does the large quantity of information now shown on PFDs need to be present at all times? Some minimal attempts to de-clutter the PFD have been made, but it can be asked whether radical

simplification of the information displayed would not be appropriate during cruising flight on autopilot.

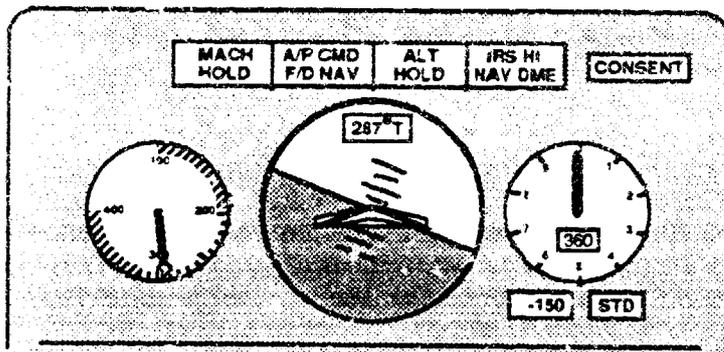


Figure 27: Simplified PFD presentation.

Such an approach is shown in figure 27, which depicts a compressed presentation of the data required under such circumstances. Research would be required to determine whether such truncated displays in fact permitted performance equivalent to present displays under all conditions, and whether detection of anomalies was as easy as with present formats. The use of different displays in different management modes might reinforce pilot awareness of the operating mode.

The primary flight display is not interactive; pilots cannot modify it, as they can the navigation displays, to suit their circumstances or cognitive styles. Whether this should be permitted, or is needed, also deserves discussion. If some degree of PFD reconfiguration or de-cluttering is to be implemented, should it be at pilot discretion or should it be done automatically as a function of flight phase or automation in use? Should a range of PFD options be available? If so, why?

Power displays: The pilot requires continuous information about the power being developed by each powerplant, and information about any anomalies in the propulsion system. Is more than this needed on primary power displays? Abbott and colleagues (ref. 61) have suggested that detection of power anomalies might be considerably enhanced by simplified displays. They point to the Air Florida 737 accident on takeoff from Washington National Airport, in which, despite conflicting information on the various engine parameters due to icing of temperature probes, the takeoff was continued with engines developing much less than takeoff thrust (ref. 68).

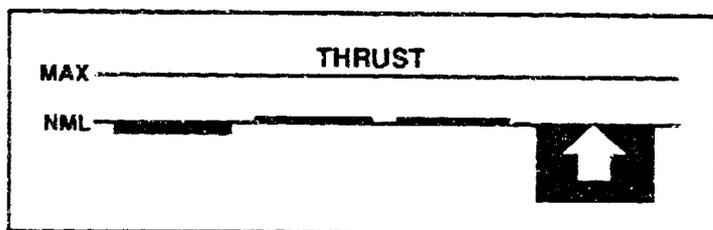


Figure 28: A simplified display of engine thrust parameters and trends. Engine 4 is still accelerating but is commanded to reach normal takeoff thrust.

As noted above, raw data on several engine parameters is displayed even in highly automated aircraft. The Air Florida case points out the importance of maintaining a scan of all of them, and the display shown in figure 22 attempts to ease this task. But what the pilot needs to know is simply the instantaneous thrust being developed by each engine, and perhaps any trends in thrust. This could be done by modern automation driving a very simple display, as shown diagrammatically in figure 28.

Configuration displays and alerting systems: Much progress has been made in simplifying alerting and warning systems. In view of their very high reliability, it is necessary to consider how pilots can be kept alert to the possibility of the failure of such systems. This has traditionally been done by relying upon pilot knowledge as the primary tool for configuring the aircraft, reinforced by the use of checklists to verify completion of the required actions. The automated warning systems are a backup check that the most essential items have been attended to. This approach has been extremely, though not invariably, successful, as the Detroit and Dallas

takeoff accidents make clear (refs. 10 and 11). Can more be done to make the system error-resistant? Each added layer of automation introduces still further complexity and expense, and more devices that can fail.

Is it necessary that we recognize the propensity of pilots to rely upon reliable automation and alter our thinking about alerting devices to recognize that they are essential to the successful functioning of air transport? This would require that essential warning systems incorporate more redundancy than they do now, so that single-point equipment failures could not compromise safety. Would such an approach further diminish the pilot's central role, or would it simply be a recognition that we have already tacitly permitted pilots to rely upon automation and that we must now build automation that will permit them to continue doing so? (See also p. 95.)

This question is raised because we are at a critical juncture. We have relied entirely upon human operators to insure that flights are completed safely, and have considered automation to be but one of a number of kinds of tools designed to assist them in their mission. Yet automation is now an *essential* tool in certain respects, as is shown by the A320 flight control system. Should primary flight control be the only case? Or should other automation applications also incorporate fault-tolerant architectures and hardware? If we consider those mishaps in which humans failed despite highly capable automation to assist them, or in which automation failed subtly, we must acknowledge that such failures are enormously expensive. If we consider all that is known about human operator error, we must concede that such failures will continue to occur (refs. 69 and 70). Are there ways to make the human-machine system more error-resistant and error-tolerant in the detection of configuration problems?

Aircraft subsystems: The MD-11 represents a benchmark in the automation of aircraft subsystem control and management. It also raises questions about aircraft control and management, as discussed on page 39-40. Leaving these questions aside, questions can be asked about subsystem operation and subsystem displays.

The issue raised on pages 25 and 26 about subsystem operating panels and switches is under investigation at this time. Whether "smart" displays with embedded control devices are technically feasible is no longer in doubt. Touch-sensitive or cursor-operated controls are commonplace. Whether they are suited for aircraft cockpits is not at all certain, and this question is confounded with issues related to safety and aircraft certification. Synoptic displays (and control media) would clearly have to be redundant if they were to become the only way of controlling subsystems. On the other hand, the coming implementation of electronic checklists on system CRT screens suggests the desirability of locating the system controls close to both the synoptics and the checklists (assuming that reconfiguration continues to be a manual operation to some degree and it probably will for critical items, and also assuming that such controls can be placed within easy reach). Crew input errors might also be less if the effect of their actions was immediately obvious on the display. What would be the new human operator costs associated with such systems?

The issue of positional familiarity was raised on page 25, but the various subsystem control panels on the overhead differ from each other; they would not differ more on well-designed synoptic screens. The lack of tactile feedback from virtual switches on a display could perhaps be compensated for by an audible click when such switches are actuated, and the operation of the switch should have a visible effect on its appearance. Control position sensing and verification is likely to be a feature of electronic checklists; this would provide an additional check against errors either or omission or commission in the performance of checklists, though recent work suggests that more automated checklists may decrease pilot awareness of system malfunctions or changes in system status, and this may be an important cost (ref. 71). Further research is underway to evaluate the benefits and costs of increased checklist automation (ref. 64).

Regardless of the approaches that may be taken in the future to aircraft system management, computer monitoring both of system status and of potentially critical operator actions to decrease

the likelihood of pilot actions that can threaten flight safety is warranted as a means of improving error-resistance (ref. 72). Such monitoring could appreciably decrease the likelihood of flight crew blunders such as those which resulted in shutting down both engines of two 767s shortly after takeoff (ref. 52), or the several instances in which fuel mismanagement has resulted in all engines failing during flight.

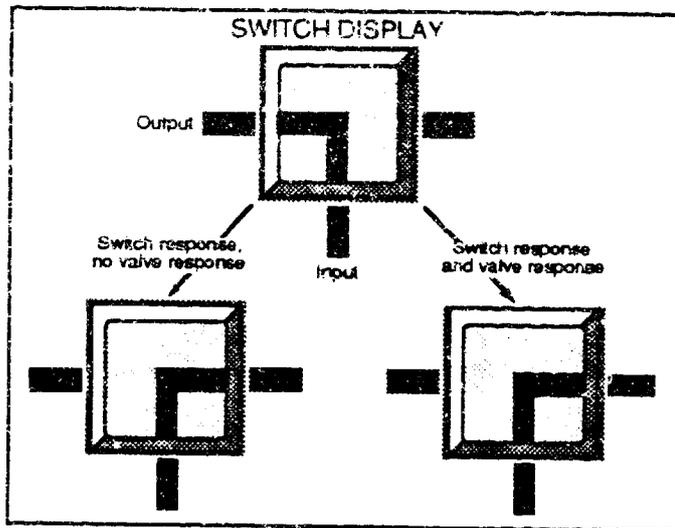


Figure 29: Electronic display of switch position and function.

The advent of synoptic displays in cockpits has given rise to another question about the display of synoptic information. On such a screen, should a switch display indicate the sensed position of the switch itself, or of the device affected? In older aircraft, disagreement between physical switch position and the control actuated was usually indicated. This can be done on CRT displays by sensing and displaying both function (flow, pressure or voltage) downstream from the switch or valve while indicating switch position on the switch icon, as is suggested in figure 29. This approach would increase display redundancy as well.

How much information does the pilot need under various circumstances? A variety of displays is used even in older aircraft, depending on how much information regarding a given function is, or may be, required (figure 30). The formats available are limited, though either dial or tape representations of data can be used. Each level of display has benefits and costs in terms of legibility, required space and weight, and mental workload necessary to assimilate the information.

The questions must always be asked: "How much information is enough? How much is too much?" Though pilots always want more information, they are not always able to assimilate it. To provide too much information simply guarantees that pilots under high workload will ignore some of it, and which data they will ignore under particular circumstances is not predictable.

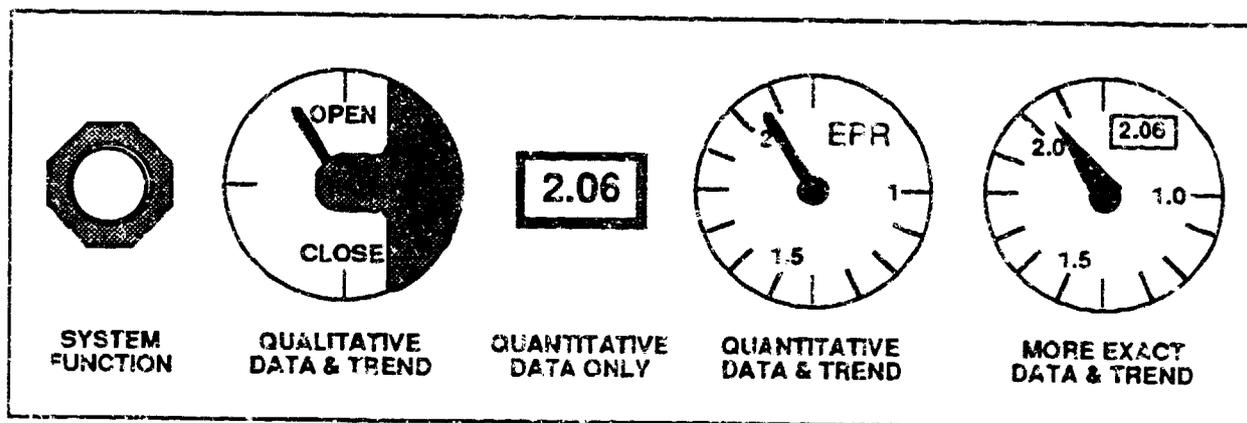


Figure 30: Amounts of information presented by various electromechanical displays.

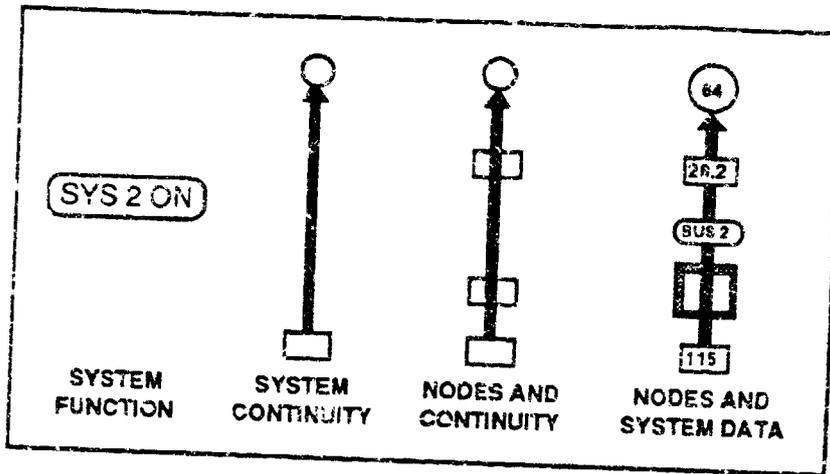


Figure 31: CRT displays of system information.

The glass cockpit has made it possible to tailor displays more effectively, and to provide alphanumeric, graphic or iconic representations of data. A continuum of displays is again possible, from the simplest indication of overall subsystem function or failure, through very simple diagrams of system continuity, to displays of systems nodes and continuity, to more complex displays that provide quantitative data regarding these functions, as shown in figure 31.

Each successive increase in display and equipment (sensor) complexity is again accompanied by a cost in human resources, as noted above (refs. 20,24,29), though the weight and space penalties of additional instruments are reduced when CRTs are used.

Pilots need much less information when subsystems are working properly than when they are malfunctioning. One possible approach to this is a hierarchy of subsystem displays: a minimum of data would be presented when a subsystem was working correctly; more data would be presented either automatically or on request when a system malfunction was detected. If touch-sensitive switches were being used, they would become available at the higher level of detail. Such an approach to a fuel system is illustrated in figure 32, which shows a greatly simplified synoptic diagram on the left, and a more complete diagram with switches for manual system operation on the right. Would such an approach provide information as needed without needlessly distracting pilots when it was not required?

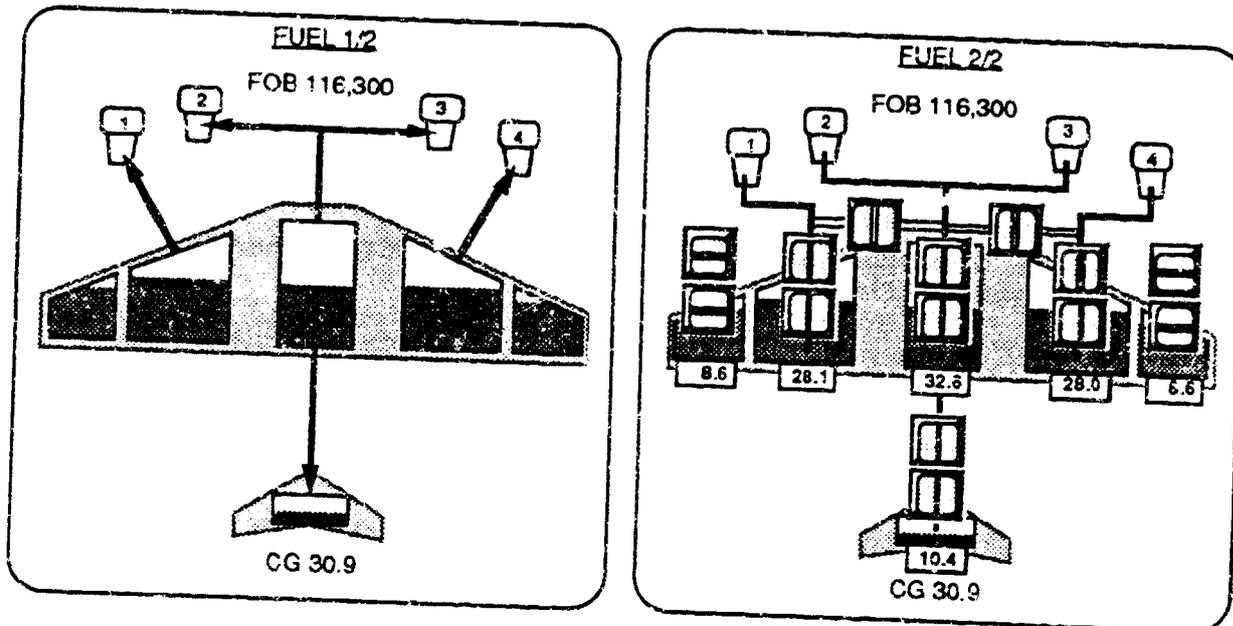


Figure 32: Hierarchy of subsystem displays: simplified fuel system synoptic at left, expanded synoptic with touch panel switches at right.

Monitoring of automation: In an automated aircraft, pilots must be able to monitor the various automation functions, as well as the functions controlled by the automation. Most current aircraft provide simple lights or lighted pushbuttons to indicate computer failures. Is this enough to insure that the flight crew remains aware of automation status and proper functioning? Or is another synoptic devoted specifically to the automation required?

As fault-tolerant automation becomes the rule, may it become necessary to indicate degradation that will not be obvious because backup channels or processors are in use? Many of the dual-processor computers in current use do not indicate to pilots that one of the two processors has failed, though the information is logged in maintenance databases and, in some aircraft, this information is accessible in cruise or on the ground. Is this information needed by pilots? It can be argued that if manual capability exists and is the backup for a total computer failure, it is only necessary to alert the pilot when manual operation becomes necessary, as in the MD-11 ASC architecture. It can also be argued, however, that pilots should be able to ascertain that the reserve capability of the automation is less because a backup processor is in use.

The Future of Information Automation

Electronic library systems, designed to reduce the amount of paper now required in transport cockpits, are under active development by at least two aircraft manufacturers and several airlines. These systems are likely to be installed in current and future generations of transport aircraft. They will probably be able to access data stored in flight management system computers, but they may not be permitted to interact with those computers to avoid certification problems.

Electronic libraries will require the addition of another dedicated CRT or flat-panel display for each pilot. If they are to be able to present graphic information in fine detail (approach plates, etc.), display resolution will be a serious issue. The organization of information and architecture of the libraries will also require considerable research to insure that information can be located quickly when it is needed, and such systems may add to the cockpit information glut.

Electronic checklists, able to reduce or eliminate paper checklists and quick reference handbooks, will also be introduced in the next generation of aircraft. Depending on their capabilities, these systems may relieve some, or a considerable part, of the routine workload of pilots. A continuum of electronic checklist automation can be proposed:

- FROM:
- 1. Paper checklists presently in use
 - 2. CRT depiction of data on checklist, with scrolling on command
 - 3. CRT depiction of checklist data with internal monitoring of status of items, and auto-scrolling
 - 4. CRT depiction of checklist with automatic execution on command of flight crew
 - 5. EICAS statement of checklist required or a problem, with execution of appropriate checklist after consent by flight crew
 - 6. EICAS statement of problem followed by automatic execution of checklist without need for action by flight crew
 - 7. Automatic checklist execution when required; subsequent status announced to flight crew
- TO:
- 8. Fully automatic checklist execution when required; flight crew not notified

This approach is similar to that proposed by Sheridan in a discussion of task allocation and supervisory control (ref. 73). The approaches currently in use in the A320 and MD-11 differ somewhat from those described in this list, though the MD-11 utilizes option 7 for subsystem reconfiguration. Electronic checklists are presently under investigation by Palmer and Degani at NASA-Ames Research Center (ref. 71). Whether pilot situation, or more properly state, awareness is enhanced by having to perform checklists is not known, though it is known that present practices with regard to checklist completion are by no means optimal (ref. 74).

Air-ground digital communications: The technology for digital communications between ground and aircraft is already in wide use (ACARS). Mode S transponder links will be as widely used within the next few years. Satellite communications will extend high-quality digital communication to aircraft flying beyond line-of-sight range from land. The bandwidth of communications channels will increase enormously, leading to the capability to transfer much more information to the cockpit.

The most important issue raised by this new capability is what information needs to be transferred, in what form, under what circumstances, and over what channels (voice or digital) for what reasons. Designers as a community need to be involved in considerations of these questions now in order to be able to implement cockpit information management in consistent and rational ways and to be able to integrate information automation into cockpit automation as a whole. There will be considerable pressure to utilize the additional capacity for information that may not be related to the critical tasks of the pilot, and this pressure must be resisted or channeled to more appropriate persons or systems. There is quite enough information in current cockpits, and not enough integration despite advances in recent years.

Management Automation

The most revolutionary changes brought about by the introduction of digital computers into aircraft automation have been in the area of flight management. Flight management systems in the contemporary sense have been in service for little more than a decade, but they have transformed the pilot's tasks during that time. In this section, we will describe the modern flight management system, the functions it performs, its interfaces with the flight crew, and the questions raised by this technology. We will suggest where flight management automation may go in the future, and what new problems may arise in this domain. First, however, we should consider briefly the environment in which aircraft management automation must operate.

The context of management automation: Until comparatively recently, airline operations as well as aircraft were largely manually operated. Flight and crew scheduling and dispatch were extremely labor-intensive. All of this has changed radically; digital computers have taken over many of the chores of flight operations management and control. Computer-generated flight plans are now devised on the basis of cost control, a critical factor especially when fuel costs are high; diversion patterns are suggested by computers when weather closes or delays operations at air carrier stations. The algorithms that drive these activities are extremely sophisticated; they take into account such variables as maintenance status of airplanes, pilot flight-hour limitations, availability of connections for passengers, and a multitude of other relevant variables. Research is now underway to enable some of these functions in the cockpit. What effects will this have on flight management? Do they belong in the cockpit, or should they remain on the ground?

Up to this time, the pilot in command of an aircraft has been the sole arbiter of its fate once it departs. The airline can communicate its strategy and its desires to the pilot, but the Captain alone decides what is best for his or her flight. Digital communications via the ARINC Communications and Address Reporting System (ACARS) have replaced much of the routine message traffic between pilots and company in some carriers, but these units until recently have sensed only a few airplane parameters used to determine and transmit times of gate departure, takeoff, landing and gate arrival (though even this limited capability brought at least one flight crew to grief when, after landing at and immediately (and illegally) taking off from the wrong airport at the destination city, ACARS automatically transmitted an extra set of "out-off-on-in" data to flight operations).

Air traffic control communication with aircraft has until now been entirely by voice. The introduction of mode S transponders (required by TCAS) with the capability to transmit and receive digital data will also introduce two-way digital data link between ATC and aircraft. Thus, digital data will be used to transmit clearances as well as company messages to airplanes in flight. (Air Canada already transmits oceanic clearances via ACARS.) Data links to flight and maintenance management systems already exist; maintenance information can be down-linked to companies. Everyone involved in the development of ATC data links to aircraft envisions the direct interaction of ATC computers and aircraft flight management computers. This introduces the potential for radical changes in the tactical control of aircraft in flight.

Although flight management automation technology itself has been brought to a high state of development, it is vital that it now be considered in the larger context of aviation system operations, for it is by no means certain what these new communications capabilities will portend for the basic allocation of roles and functions that has characterized past air transport operations. The implications for the humans who operate in the system are enormous.

Flight management system functions: Contemporary flight management systems are complex computational devices linked to and communicating with a great many other aircraft systems as well as with the pilots. Figure 33 shows this diagrammatically for the MD-11 FMS (ref. 75). FMS software, resident in a flight management computer (FMC), includes an operational program (containing, in this case, over 1400 software modules), a navigation data base, and a performance data base for the aircraft in which it is installed.

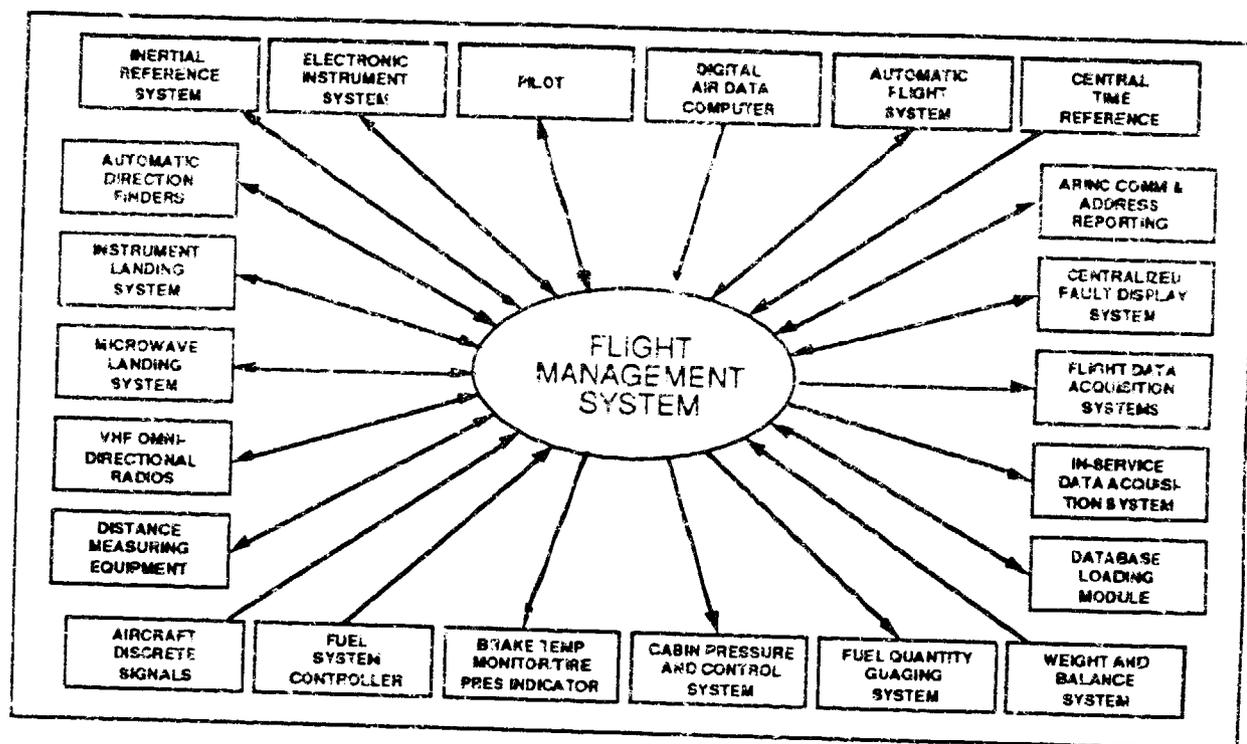


Figure 33: Interaction of flight management computer with other aircraft avionics (Honeywell FMS for MD-11).

The FMS software executes these functions:

Navigation	Automatic radio tuning, determination of position, velocity and wind.
Performance	Trajectory determination, definition of guidance and control targets, flight path predictions.
Guidance	Error determination, lateral steering and control command generation.
Electronic instrument system	Computation of map and situation data for display.
Control-display unit	Processing of keystrokes and flight plan construction.
Input/output	Processing of received and transmitted data.
Built-in test	System monitoring, self testing and record keeping.
Operating system	Executive control of the operational program, memory management, and stored routines.

The FMC navigation data base includes much of the information the pilot would normally determine by referring to navigation charts. This information can be displayed on the CDU or CRT map. The geographic area covered includes all areas where the airplane is normally flown. The data base, tailored to specific airline customers, presently contains 32,500 navigation points and airway route structure data. The stored data includes the location of VHF navigation aids, airports, runways, geographical reference points, and other airline-selected information such as standard instrument departures, standard arrival routes, approaches and company routes. Up to 40 additional waypoints can be entered into the data base by the pilots.

The FMC performance data base reduces the need for the pilot to refer to performance manuals during flight; it provides speed targets and altitude guidance with which the flight control computer develops pitch and thrust commands. The performance data base is also used by the FMC to provide detailed predictions along the entire aircraft trajectory. The data stored in the data base includes accurate airplane drag and engine model data, maximum altitudes, and maximum and minimum speeds.

Functions performed by the FMS include navigation using inertial data from inertial reference units aboard the airplane and a combination of radio aids where available. It provides lateral guidance based on a stored or manually entered flight plan, and vertical guidance and navigation during climb and descent based on gross weight, cost index, predicted winds at cruise altitudes, and specific ATC constraints.

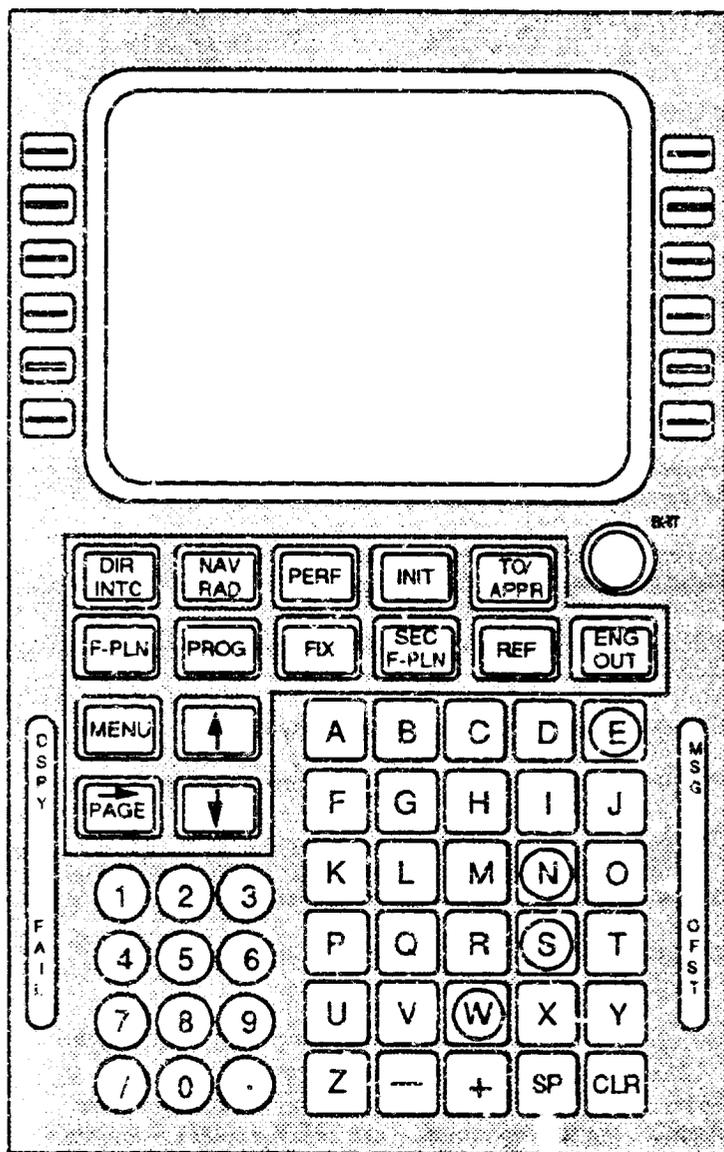


Figure 34: Honeywell FMS control and display unit, MD-11.

Flight management system controls: Interaction with all flight management systems is through a control and display unit (CDU) which combines a monochromatic or color CRT or LCD screen with a keyboard. An example of a CDU is shown in figure 34.

The unit contains a CRT display screen, six line select keys on each side of the CRT, a brightness adjust knob, 15 mode select keys, two annunciators on each side of the keyboards, an alphabetic keyboard, and a numeric keyboard. The mode select keys provide quick access to FMS function pages and data; the alphanumeric keypads permit entry of data into the computer.

The newest FMSs provide a number of routines to minimize pilot workload. Among them are the "ENG OUT" function, which provides automatic or manual access to the flight plan (F-PLN) or performance (PERF) pages to assist in evaluating and handling an engine failure condition. The function enables FMS engine-out operation modes.

Entry of data is accomplished by using the keypads. The entered data are shown on a scratchpad line (see below); when a line select key is pushed, the data are transferred to the indicated line if they are in a format acceptable to the computer.

Flight management system displays: The CDU display consists of a large number of "pages," each containing up to 14 lines of alphanumeric information as shown in figure 35.

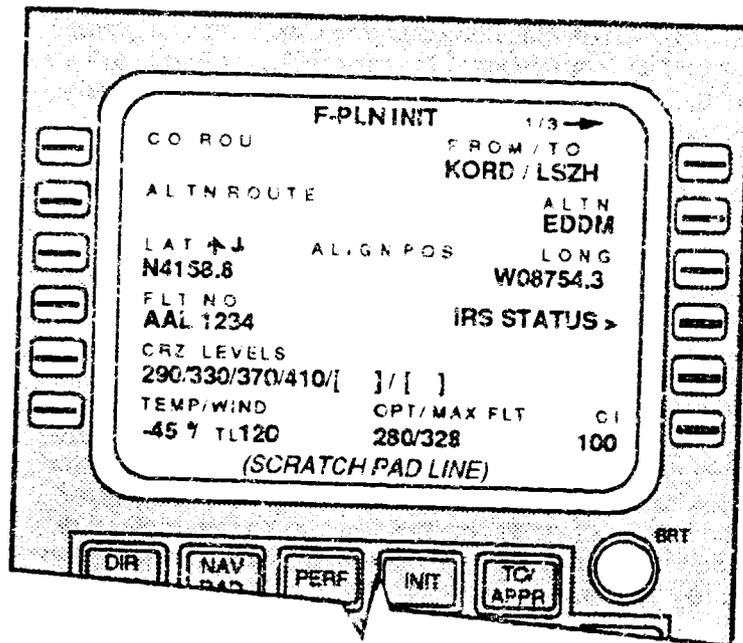


Figure 35: Control and display unit screen, MD-11.

The CDU screen shown here is the one that would appear when the "INIT" mode select key is actuated. The title line, at top, shows that this is the first of three flight plan screens; the others may be accessed with the PAGE key. The scratch pad line is at the bottom of the display. Vertical arrows indicate that the arrow keys may be used to increment values. The small font displays are predicted, default or FMC-calculated values, and labels.

The 50 CDU pages are arranged in a "tree" architecture. Portions of the architecture are accessed by 12 of the mode select keys. A portion of this logical, but complex, architecture is shown below in figure 36.

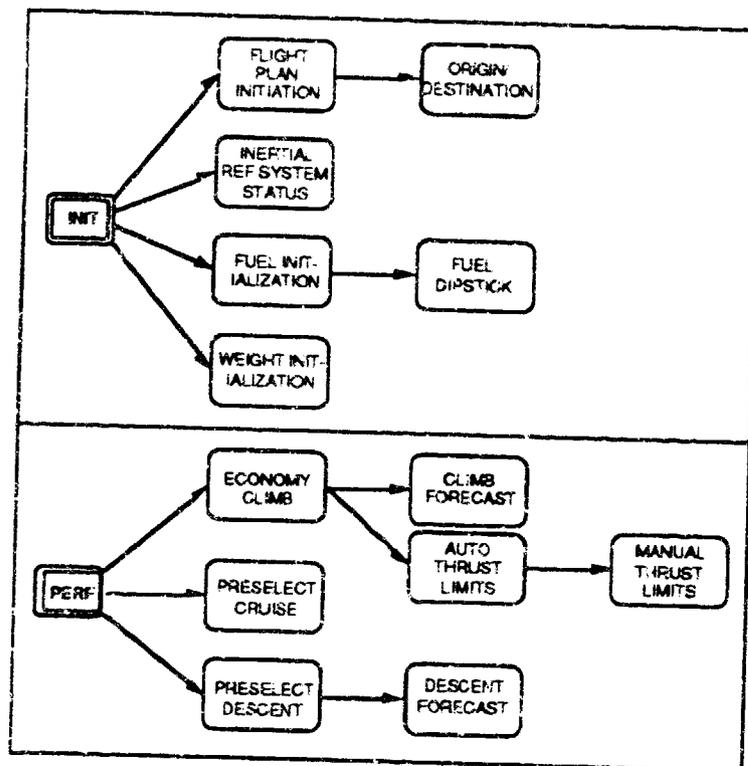


Figure 36: FMS mode screens, MD-11.

These diagrams show the tree structure for two modes of this FMS. There are 12 such structures. While each is logical within itself, studies have shown that the actual number of necessary paging sequences is much larger. In a study of another FMS of the same generation, it was found that the number of sequences was several times the number planned for by the manufacturer (ref. 76). These structures, as well as the displays, vary greatly among aircraft types and avionics manufacturers.

This large number of potential trees involves a considerable attentional demand upon the pilot, even if he or she is fully proficient in the use of the FMS. Since flight plan changes are most commonly required during departure and arrival, reprogramming the FMS can divert a significant amount of attention that may be needed for outside scan and for cross-cockpit monitoring.

Discussion of Management Automation

Flight management system operation: Both pilots may interact with the MD-11 FMS simultaneously; however, the system will accept flight plan modifications only one at a time. There are two FMCs, each of which may accept data from either CDU; one FMC is designated as master, and both must confirm data entry before new data will be accepted. The two computers communicate with each other through a private data bus.

In all FMSs, the complexity of the mode and display architecture poses substantial operational issues. Much has been done to simplify routine data entry, but recovery from errors in programming can be difficult. Entry of certain types of data remains cumbersome and time-consuming and diverts attention from other flying tasks, as discussed below. If an incorrect entry is attempted, it is rejected, but without explanation of the error that led to the rejection, as one instance.

All interaction with the FMS is through one of two or three identical CDUs mounted on the center console. Even with color to assist, operation of the FMS requires close visual attention to the screen, and precision in entering data on the keypads. Alphanumeric data entry is known to be subject to human errors: numbers may be recalled incorrectly from short-term memory (transposition is most common), they may be input incorrectly, or they may be misread when the entries are verified in the scratchpad before entry into the computer. Some data must be entered in a specific sequence which imposes additional memory load on the operator; screen prompts are not always clear, when they are available.

Avionics and aircraft manufacturers have made many efforts to make interaction with the FMS more error-resistant. Standard or frequently-used routes are stored in the navigation data base and may be recalled by number. SIDs and STARs are also in the data base; if a change is required by ATC, only the name of the procedure need be entered. Changing the arrival runway automatically changes the route of flight. Appropriate navigation radio frequencies are auto-tuned as required. Perhaps most important, newer FMSs interact directly with navigation displays; pilots are shown the effect of a change of flight plan in graphic form. They can thus verify that an alternative flight plan is reasonable (though not necessarily what was requested by ATC) before putting it into effect.

In some new aircraft, entry of tactical flight plan modifications (speed, altitude, heading, vertical speed) can be done through the mode control panel rather than the CDU. These entries may either supersede FMS data temporarily, or may be entered into the FMS directly from the panel. Experience with these improvements has been limited; it is thought that they may resolve some problems with tactical data entry, though pilots must keep track of more potential mode interactions.

Vertical navigation profiles generated by the FMS take account of standard ATC altitude constraints as well as airplane performance constraints, though the air traffic control system is not, at this time, able to take full advantage of the capabilities of management automation which calculates profiles based on actual rather than best average aircraft weight. Optimal descent profiles will therefore differ enough to cause sequencing problems for ATC.

In newer aircraft, manual tuning of navigation radios is possible only by interacting with the CDU. Many pilots have complained that alphanumeric entry of frequency data is more time-consuming and requires more prolonged attention inside the cockpit than setting the rotary selector knobs in older aircraft.

Though flight management systems truly permit pilots to manage, rather than control, their aircraft, the dynamic nature and increasing congestion of today's operational environment has

strained the capabilities of the human-machine interface (see below). Despite this, the systems are extremely effective and have enabled many improvements in operational efficiency and economy.

Flight management system displays: The greatest improvement in FMS display capability has been its integration with aircraft navigation displays, freeing the systems from some of the constraints imposed by small alphanumeric CRTs. The addition of color to the CDU display (early displays were invariably monochromatic) may help, though the resolution of the color displays is less and the usefulness of color in this application has not received much systematic study. The design of pages, however, still represents a compromise between the amount of alphanumeric data per page and the number of pages necessary to enable a particular function.

As shown above, the displays are complex and the number of pages is large. The attention required for re-programming has led to undesirable *ad hoc* procedures in the cockpit; an appreciable number of pilots prefer not to interact with the systems below 10,000 feet during descent, in order not to compromise aircraft management and scan for other traffic (ref. 19,77). This approach permits human resources to be devoted to more important tasks, but at the cost of losing some of the benefits of the FMS during flight in the terminal area (such as its knowledge of altitude restrictions). This is clearly a problem of human-system interface design, rather than a problem in the design of the systems themselves. A number of research and development efforts are underway to improve these interfaces and specifically to make them less totally dependent on cumbersome alphanumeric data entry, but considerable attention to the CDU displays is also warranted. There remain important questions about the integration of these systems into the overall cockpit and automation design, and it is these integration issues that most need to be resolved.

The Future of Management Automation

Flight management systems have been brought to a highly-advanced technological state in a very short period of time. New systems will be able to take advantage of new navigation aids, in particular satellite navigation, without appreciable further development. Future systems may provide further assistance to pilots by providing autotuning of communications, as well as navigation, radios when new communications frequencies are uplinked to aircraft by data link; this means of communication will also become the channel through which clearances and subsequent amendments are transmitted to aircraft, and may become the primary means by which pilots assent to or request modification of such clearances.

It is this technology and the uses that will be made of it that raises the most serious questions concerning the future of management automation. Data linked clearances will require only consent from pilots to be entered automatically into the FMC, and acted upon thereafter. Will pilots fully consider the potential impact of a clearance change before accepting it? Will they be as aware of its impact given the ease with which new clearances can be transferred to the FMS? Will situation awareness be maintained? When the airplane is being manually controlled, will the flying pilot, whose visual attention is largely centered on the flying task, be fully aware of the changes when they are presented visually, rather than by voice as is the case today?

Pilot refusal to accept a new or amended clearance, on the other hand, will require negotiation between the pilot and controller. How will such negotiations be conducted? Will they be between aircraft and ATC computers, or will voice communications be used in such cases? If between computers, how will the pilots (and controllers) remain directly involved? How will intent be communicated between the pilots and controllers? If the negotiation process is slow or onerous, some pilots will be tempted to simply accept a clearance rather than argue about it, especially when their workload is high. Ways must be found to avoid such problems.

Will the correct reception of uplinked data be verified with the ATC computer before the data are acted upon by the FMC? How will errors in automatic clearances be detected? This is a difficult problem under high workload conditions today; errors in clearance readbacks are not

infrequently missed by controllers if indeed there is time between transmissions to read them back (ref. 78). Will the architecture of the new communications systems be designed to improve error resistance?

Error resistance could be materially improved by comparison of pilot-entered FMS data with clearance amendments, and by comparison of critical data in the FMC with ATC computer data to verify that an airplane is indeed proceeding in accordance with ATC's intentions for it. This could drastically decrease the large number of altitude excursions that occur in the present system (ref. 79), and most important, could prevent many such excursions before they occur rather than detecting them only after they occur. Advanced ATC automation will look much farther into the future to detect potential conflicts and resolve them prospectively (ref. 80); if the FMC is to communicate with ATC computers, new methods of detecting and especially of avoiding potential future errors also become possible and should be considered.

It is clear that the integration of the air and ground elements of the aviation system will proceed at an accelerating rate. At this point in time, when the architecture of the more integrated system is being developed, all system participants should be considering how to improve system safety by increasing error resistance and error tolerance, both by more effective digital communication and by including data that can be used for error detection and mitigation. If this is not done prior to ATC data link system design, it will be much more difficult later.

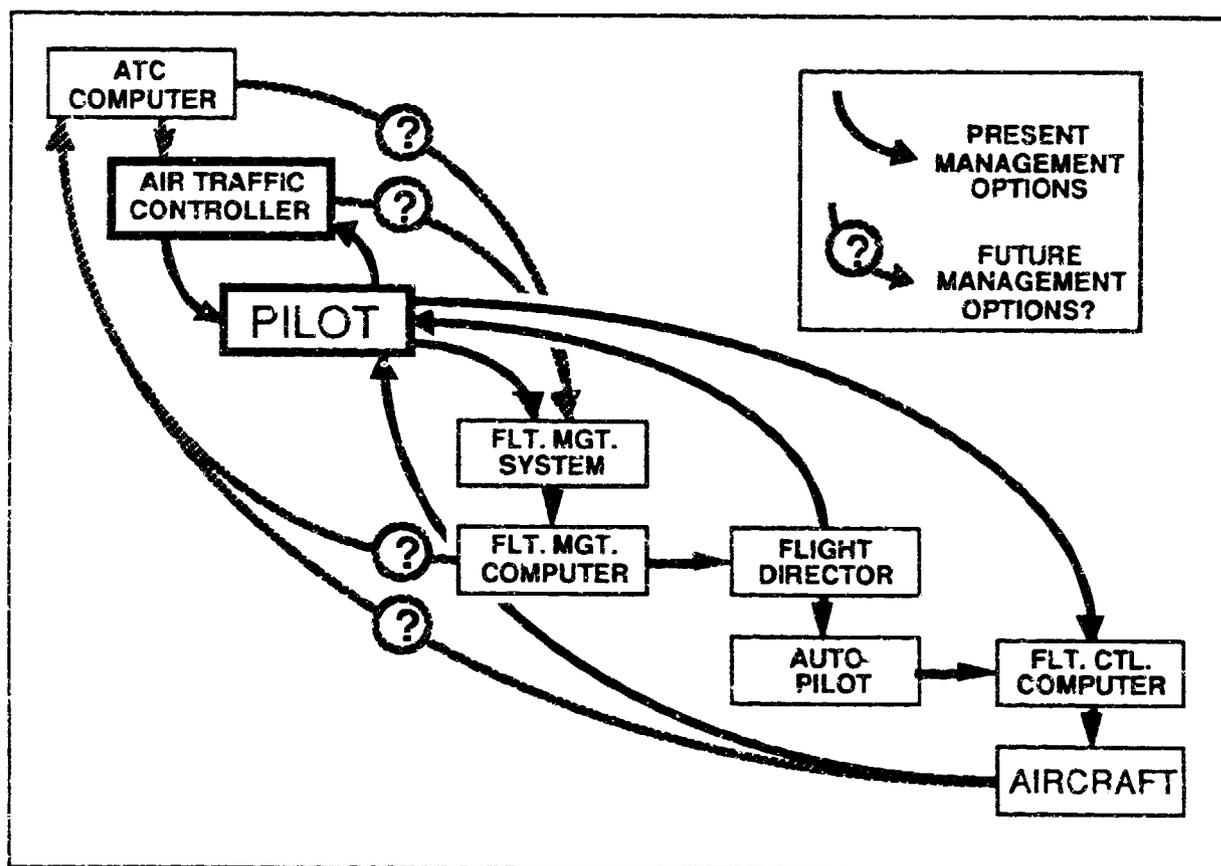


Figure 37: Present and future options for management of air traffic.

Questions regarding future management automation do not relate to flight management as it is now accomplished, but rather to the respective roles of the humans and computers (figure 37). At this time, the pilot closes the flight control and management loops. The coming availability of data link between aircraft and air traffic computers creates the potential for other management options

that remove the pilot and controller from the loop, however. Will there be pressure to utilize those options? It is accepted that humans will retain full responsibility for system safety. Will they, however, remain in full command of the more automated system?

For that matter, will command of that future system even remain within their capabilities? A recent MITRE study of AERA 2 (Automated En Route Air Traffic Control) (ref. 80) outlines high-level operating guidelines for air traffic controllers when AERA 2 becomes operational in 1999. It states that,

"Responsibility for safe operation of aircraft remains with the pilot in command

"Responsibility for separation between controlled aircraft remains with the controller.

"Since detecting conflicts for aircraft on random routes is more difficult than if the traffic were structured on airways, the controller will have to rely on the (automated) system to detect problems and to provide resolutions that solve the problem.

"Alerts may be given in situations where later information reveals that separation standards would not be violated...This is due to uncertainty in trajectory estimation...Therefore, alerts must be given when there is the possibility that separation may be violated, and the controller must consider all alerts as valid."

In its Executive Summary, the report states,

"Machine-generated resolutions offered to a controller that are free of automation-identified objections are assumed feasible and implementable as presented.

"The controller will use automation to the maximum extent possible."

It is far from clear that air traffic controllers in the AERA system will be *able* to exercise more than limited authority, but it is quite clear that they will continue to be fully responsible for the safety of air traffic. Will advances in air-ground automation place the pilot in a similar position? More appropriately, given the concept of human-centered automation set forth at the beginning of this document, how can we design and operate human-centered automation so that this does not happen?

III: THE ENVIRONMENT OF AIRCRAFT AUTOMATION

Introduction

It is not sufficient to consider aircraft automation independent of the environment in which it exists and is used. All tools are products of the societies and technologies and individuals which developed them; aircraft automation likewise is a product of the environment and context within which it was developed, and it is a tool for the people who operate and manage the aviation system. Aviation is somewhat different from manufacturing, however, in that the production units may be both operated or controlled, and managed, by the same persons. To that extent, both manual and cognitive skills are required to be resident in the same operator, and the sharp division between "doing" and "thinking" that characterizes Taylor's scientific management notions (ref. 81) is not present.

The European ESPRIT program emphasizes the "human-centered workplace", and much research that preceded it or has been done under its auspices has been motivated by sociological and cultural concerns (ref. 82). This is relevant in this context, because in aviation more than in most endeavors, the concept of social "class" is blurred. The workers, to a considerable extent, are also the managers in flight operations and in air traffic control as well, and failure to recognize this duality has brought more than a few operations to grief. Despite the best efforts of those who seek a clear demarcation between labor and management, pilots and controllers alike persist in acting in both capacities and do not, on the whole, behave consistently as one or the other.

In this section, we consider the context of aircraft automation: the vehicles, the physical environment and the operational environment in which they fly, and the people who operate them. All have changed considerably in recent years and will change further in the near future. To remain an effective resource, aircraft automation, now an essential tool for aviation system safety and productivity, must take account of these changes.

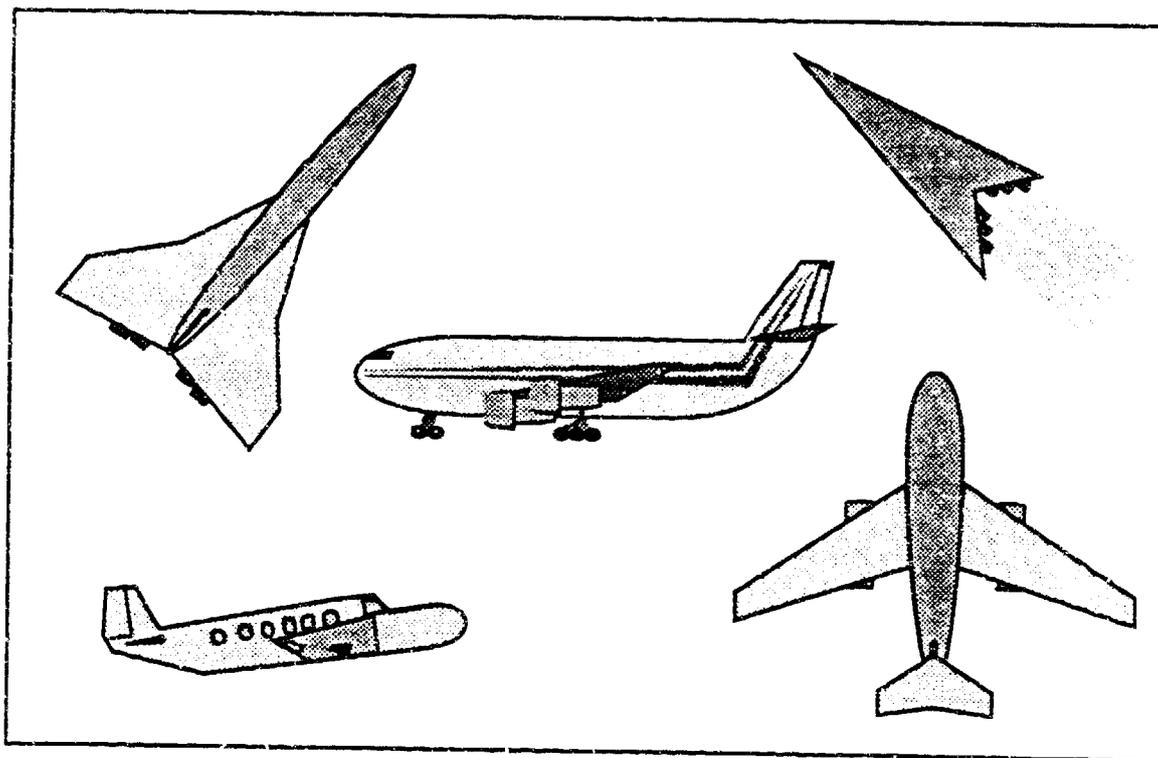


Figure 38: Aircraft in the future system.

The Aircraft

Throughout this section, it must be remembered that the advanced aircraft designed and built during the last ten years will be in service for the next twenty or more years. To a considerable extent, the shape of the future can be seen in daily operation at any of our large airports (figure 38). For this reason if for no other, it is thought most changes in the vehicles will be evolutionary, not revolutionary, during the next 10-15 years.

An important exception may be a new supersonic transport which could vastly improve service along the Pacific rim, transporting economically large passenger loads in less than half the time presently required. Having said this, however, it is necessary to recall that the *Aerospatiale Concorde* has been in daily service between the United States and Europe for over twenty years, and that without a fatal accident. *Concorde* does not carry economically viable numbers of passengers, but it was the first fly-by-wire civil aircraft, it incorporated the forerunners of some of today's advanced automation, and it too will remain in service for a considerable time to come.

The changes in cockpit and automation technology during the past decade have been as revolutionary as the changes in aircraft technology during the 1950s, when jet transports were introduced into air transport. At the beginning of the 1980s, transport cockpits contained electromechanical instruments, competent autopilots and autothrust systems, and radio and inertial navigation systems of limited capability. Communications were almost entirely by means of voice. Pilots could manage their aircraft by delegation of duties to the autoflight systems and, in equipped aircraft, they could insert flight plans into the inertial navigation systems. Vertical navigation was still accomplished manually.

Ten years later, pilots are still responsible for manual guidance of their aircraft—but only from the gate to the runway, and from the runway threshold through the takeoff. If they elect to do so, they can resume manual control only after the aircraft is again on the runway at its destination. They must still instruct the automation how to conduct the flight, though even these instructions will be able to be communicated directly to the FMS in the near future. Initial testing of data link communications through satellites over the Pacific began at the beginning of 1991. Tests of ATC pre-flight clearance delivery via data link were already in progress at that time.

Aircraft were once used almost exclusively for one type of mission, either short-haul or long-haul transportation. More flexible management styles, enabled largely by airline automation, have blurred this distinction. An airplane designed for very long routes may well conduct flights of very short duration at either end of its longer flights; these short flights may be one hour or less in length. "Short-haul" aircraft may now conduct trans-continental operations of five or more hours when loads are light. Cockpit equipment and procedures, once very different in the two types of aircraft, differ much less in present-day aircraft and will differ still less in future derivative and new designs. High levels of automation, formerly installed only in long-haul machines, are now found to an almost equal degree in short-haul cockpits.

Aircraft fly much more these days. In a regulated air transport environment, aircraft flew, on average, perhaps 6-8 hours out of each 24. Some airlines have now doubled these figures by optimization of scheduling. This has meant profound changes in maintenance scheduling and in aircraft equipment; the economic penalty of keeping an airplane on the ground awaiting maintenance is simply too great to permit grounding the machine for any but serious malfunctions. Redundancy of systems has increased greatly and dispatch of aircraft with inoperative components awaiting repair has also increased greatly. This has been a source of contention between pilots and airlines, but like so many other changes which have occurred in the wake of deregulation, it is a fact of life. It does require pilots to be prepared to undertake flights without some of the equipment which they have become used to having, nowever, and to that extent they may be required to adapt to a variety of operating and management styles even within a single flight sequence.

Indeed, the proliferation of aircraft models within a single type and carrying a single type certificate has also posed potential problems. During a flight sequence pilots in some carriers may fly both early (1970 vintage) and just-delivered modern variants of the same aircraft, carrying vastly different amounts of automation, instrumentation and other cockpit aids. The enormously successful Boeing 737 series, of which more than 2000 have been delivered between 1967 and the present, spans the entire development of advanced automation. The MD-90 carries the same type certificate as the original DC-9-10, first delivered in 1963, and pilots in some airlines may fly several of its seven models. Pilots are given differences training to acquaint them with the features of the various models, but cockpit operations may differ substantially across models, some of which may contain modern flight management systems while others have only a simple autopilot and fully manual subsystems.

The Physical Environment

Though aircraft have changed dramatically, they are still operated by "Mark I" humans in a "Mark I" physical environment. What has changed is the amount of pressure on airlines to maintain schedule regularity in the face of uncontrollable variations in weather (figure 39). The increase in aircraft flying hours on tighter schedules and the growing use of the "hub-and-spoke" concept of airline operations have imposed increasingly severe penalties for delays and diversions. A single non-arrival at a hub early in the morning can affect as many as ten departures later in the day. Airline gates are in short supply, particularly at hubs; this again increases penalties for a late (or even an early) arrival.

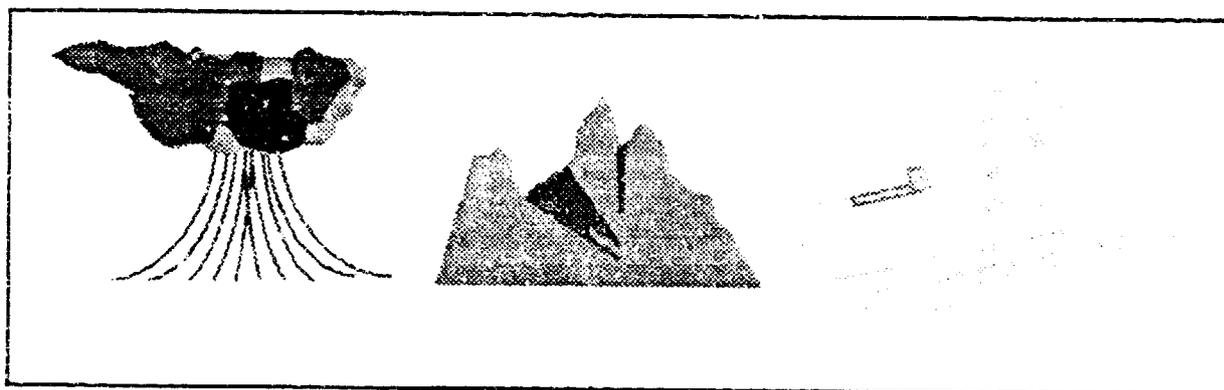


Figure 39: The physical hazards: thunderstorms, high terrain, snow.

Though pilots still remain the sole arbiters of their operations when safety is threatened by weather or unfavorable runway conditions, the tighter economic climate, reinforced by the demise of many inefficient carriers, has affected everyone in the air carrier industry. Airlines and pilots alike find themselves forced to operate profitably in a real world whose physical constraints have not changed. They have done so in part by gathering and disseminating more and better information about the state of the physical environment, in part by the use of automated scheduling and planning aids, and in part by utilizing the flexibility of the human operator, who remains the primary defense against operations beyond safe limits that may be difficult to discern at the time. This defense has not always been effective, as was shown in a Delta Airlines L1011 accident following a microburst encounter at Dallas-Fort Worth (ref. 83). That they have usually been able to do so in the face of unrelenting pressure says a great deal about the effectiveness of airline training and supervision; it also says a great deal about the effectiveness of regulatory and certification authorities in setting reasonable but safe minimum standards for air transport.

The Operational Environment

Under this heading, we include both the air traffic management system and the flight operations systems of the various air carriers; each impose rules and limits within which pilots must operate. The air traffic management system manages and controls all movements of air carrier aircraft. Air carrier flight operations systems, operating within constraints imposed by air traffic management, provide a continuing feed of aircraft to the air traffic system (figure 40).

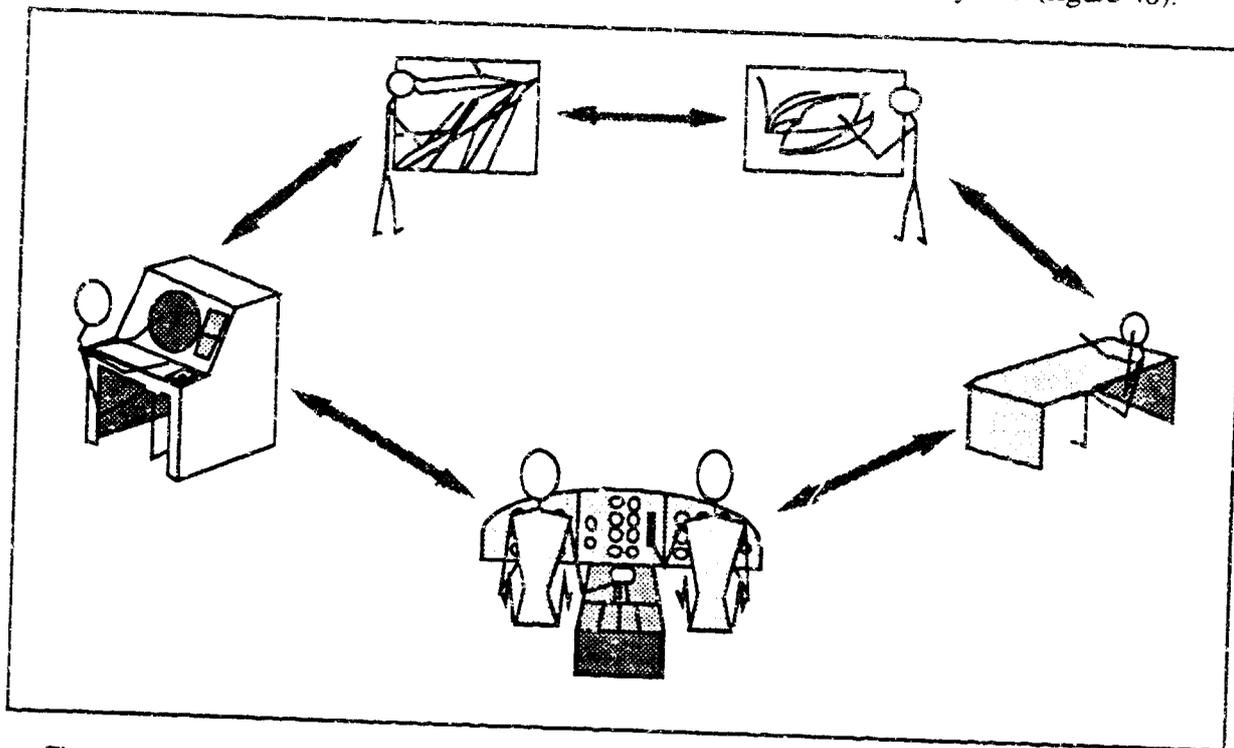


Figure 40: Management of air traffic is shared among Flow Control, ATC, Airline Scheduling and Dispatch.

Though tactical air traffic control is still largely a manual system (this will change to a profound degree during the coming decade), strategic air traffic management has been automated to a considerable degree. Flow management, designed to insure that the ATC system does not become seriously overloaded, now determines capacity at heavily-used airports and redirects the flow of air traffic during contingency operations forced by weather, runway closings, or emergencies in progress. It provides the constraints under which the entire system must operate.

The original impetus for "flow control" was the fuel crisis brought about by the Arab oil embargo in 1974. The costs of holding in flight (essentially circling at a waypoint while awaiting a landing slot at a congested airport) became unbearable and efforts were made to hold aircraft on the ground at their points of departure. The near-collapse of the ATC system during the controllers' strike in 1981 forced the Federal Aviation Administration to impose draconian limits on the capacity of the national airspace system; flow control was the primary means through which the system was able to operate within the capabilities of the severely depleted ATC facilities. The steady increases in air carrier traffic during the 1980s, coupled with the painful recovery from the strike, again strained the capabilities of the airspace system; flow control, considerably improved and increasingly automated, provided the strategic airspace management capability which has enabled the system to absorb continuing increases in traffic, albeit with increasing numbers of delays at airline hubs.

The work of flow control is largely transparent to individual pilots, though those who are delayed in departure due to mechanical or other problems may perceive its operations as delays

obtaining a takeoff slot. Not so the ATC system, which controls literally every movement of every air carrier airplane from gate to gate. Air traffic controllers and pilots together are the operators of the system; they share responsibility for safe mission completion.

Air traffic controllers operate a largely manual air traffic control system under an extremely comprehensive set of rules and procedures designed to cover virtually every eventuality that may arise in the conduct of flight operations. Though controllers have been freed to some extent from purely procedural control of air traffic by the advent of radar and altitude-encoding transponders which provide them with three-dimensional indications of aircraft locations, constraints imposed by the increasing volume of air traffic still force them to work largely by inflexible rules, a source of continuing annoyance both to them and to pilots who are unable, by virtue of those rules, to operate as efficiently as they would like to and as their airborne automation would permit them to. The discrepancy between airborne equipment capabilities and the ability of ATC to permit the use of those capabilities has increased and become more obvious since the introduction of highly-automated aircraft with vertical navigation options.

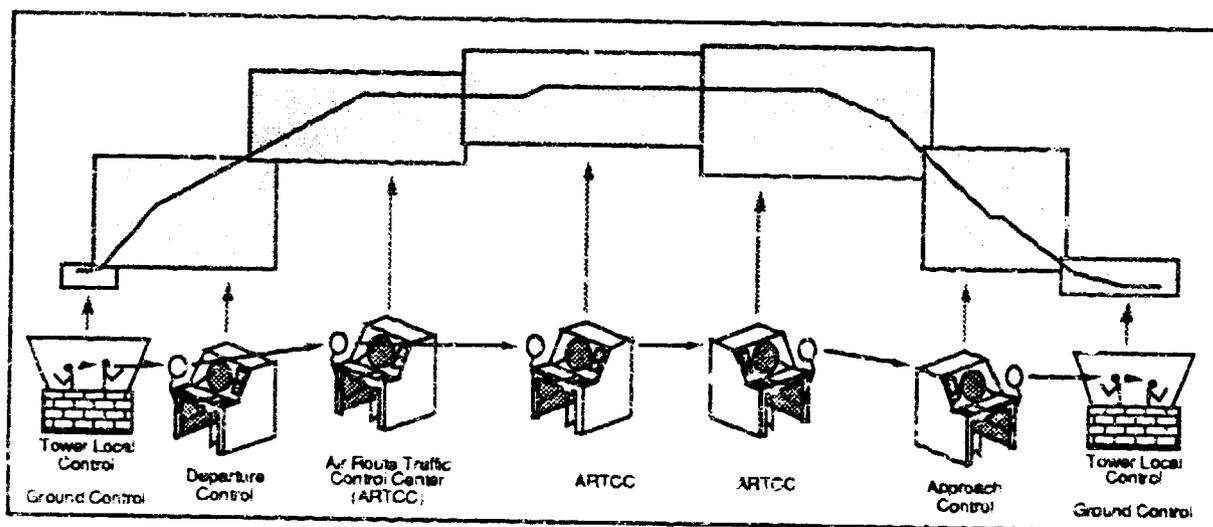


Figure 41. The air traffic control system.

The inherently manual nature of air traffic control forces it to operate in a highly orderly manner (figure 41). The present system is highly intolerant either of disorder or of human error, as was tragically demonstrated in two recent collisions between two aircraft on runways at Los Angeles and Detroit (ref. 84). Incident reports demonstrate that in-flight emergencies also, while generally well-handled, may in turn precipitate other problems involving other aircraft (ref. 85). Indeed, the ability of the system to handle anomalies is largely due to the flexibility of its human controllers, who demonstrate great professionalism and skill in their conduct under difficult circumstances.

The FAA has embarked on a major re-equipment program to provide ATC with better tools with which to conduct its operations. Massive automation of the ATC system during the next two decades will permit the limited capacity of U.S. airspace, and particularly its heavily-congested terminal areas, to be utilized to the fullest extent possible, though without new runway capacity the airspace system will continue to be under severe strain into the foreseeable future. As indicated in the previous section, ATC automation will force drastic changes in the role of the air traffic controller; it may also cause major changes in the processes by which air traffic controllers and pilots have worked together to accomplish the mission.

Not all of these changes will be bad, by any means; the automated en route system should be able to accommodate pilot and company route preferences much more often than is now the case.

AERA by itself will not, however, be able to improve terminal area operations appreciably, and research is now underway both within FAA and NASA to assist terminal area traffic management by providing controllers with automated decision aids to improve arrival traffic flows (ref. 64,86). If, however, an automated ATC system inhibits the ability of controllers and pilots to work cooperatively to resolve problems, it will severely limit the flexibility of the system, and the loss of that flexibility could undo much of the benefit expected from a more automated system.

Unfortunately, the gains in capacity from improved airspace usage will be limited at best without new runways or radical differences in operating methods. The social and political problems posed by new airport construction have thus far seemed insurmountable, despite the growing dependence of the public on air transport for both the conduct of its business and its leisure (ref. 17). This problem is beyond the scope of this document, but the fact that it has thus far been insoluble is forcing aircraft to operate to tighter and tighter tolerances. Separation standards long considered inviolate have been relaxed in the Los Angeles and six other terminal areas; FAA and NASA will shortly begin to examine ways of permitting aircraft to conduct much more closely-spaced parallel or converging approaches to landing under instrument meteorological conditions (ref. 87). The latter change may be enabled, in part, by new collision avoidance displays, along with better ground radar, but it may also require more automated operations under these conditions, and both changes will certainly require higher levels of vigilance and will probably place higher cognitive demands on pilots and controllers alike.

It should be noted that the rules and regulations governing air transport have not been conclusively proven to be "safe enough" to produce an extremely safe system, though most of the accidents that occur are due to contravention of those rules and regulations or to errors in carrying them out. But we do not know how much of a margin of safety is embodied in those rules, for air carriers and ATC have usually operated to a standard somewhat higher than the rules require. We are now being forced by increasing traffic congestion to operate to the limits of the rules for air traffic management, and in some carefully-considered cases to relax them. This is an exercise fraught with peril and it must be approached with the greatest care, tempered by common sense and careful research and operational testing. Improvements in automation technology can help humans to accomplish new and more difficult tasks, but automation should *not* be used to increase system throughput beyond the limits of human capability to operate manually in the event of automation failures if humans are to remain fully responsible for system safety. There is increasing evidence that this could be allowed to happen during the coming decade, at least in air traffic control.

The Human Operators

In considering the context of aircraft automation, the most important facet is the human being who operates, controls or manages that automation in the pursuit of human and social objectives. Though in a previous section we made reference to improved aircraft still operated by the "Mark I" human, this is true only in a general sense. Individual human capabilities have not changed very much in the short history of aviation, but human operators, considered collectively, have changed a great deal, in the course of learning to design and understanding how to operate the advanced technology that characterizes aviation.

An unprecedented expansion of air carrier flight operations during the 1980s, coupled with a decline in the number of available military pilots and changes in Federal regulations concerning hiring, has precluded the carriers from continuing to rely almost totally on fully-trained military pilots for their new entrants. Persons without military experience, often with more limited aviation backgrounds, have been hired in large numbers in recent years. A large proportion has come from the ranks of commuter airlines, some of which have regularly experienced turnover of well over 50% per year because of this. More women, minorities, and older persons have been permitted to enter the air carrier work force. The overall complexion of the air carrier pilot population is changing more rapidly than at any previous time in history.

Though this has had many effects, good and bad, it has meant that airlines can no longer assume a common pool of shared experience in their new pilots. They must therefore develop a shared adherence to their desired standards through new-hire training, initial operating experience, and continued training in line operations. Airlines have always relied upon their captains to conduct much of their training, and the system has worked well, but airline expansion has also meant that pilots progress much more rapidly to captain status; for this reason, captains also may have less experience than their counterparts of a decade ago. These factors, rapid progression through different seats and different airplanes, and other related factors pose another threat of a different sort to operational safety. The NTSB has commented unfavorably on the pairing of crew members, both with very limited experience in the aircraft being flown, in several accidents, notably a Continental Airlines DC-9 takeoff accident at Denver (ref. 88) and the US Air B-737 takeoff accident at LaGuardia Airport in New York (ref. 89).

Experts solve problems quite differently from novices (ref. 90). As we train a more heterogeneous population of air carrier pilots, we must also train problem-solving skills, a topic we have tended to take for granted in the past. In particular, it will be necessary to train at least some of the new entrants in problem-solving under time pressure, a task for which cockpit procedures trainers and more capable simulators are well-suited.

Each of these factors makes rule-based operations a virtual necessity; the imposition of standard rules and standard operating practices can do much to maintain uniform operating standards in a diverse group of people. Beniger points out, however, that while "programs control by determining decisions", Godel's incompleteness theorem says that in any formal system there exists an undecidable formula, and that the consistency of such a system is also undecidable (ref. 91). Cooley also discusses the "de-skilling" effect of automatizing behavior and derides the "American fallacy" of "the one best way" (ref. 92).

Humans are not automata, and it was noted above that pilots, in particular, persist in behaving both like operators and managers. Too much reliance on rules produces both a decrease in incentive and over-reliance on set behavioral formulas in an environment in which the unexpected can be confidently predicted to occur. The point of this is that while standard operating procedures are necessary and desirable, they cannot in all circumstances be considered a substitute for what our British colleagues call "airmanship": the ability to act wisely in the conduct of flight operations under difficult circumstances.

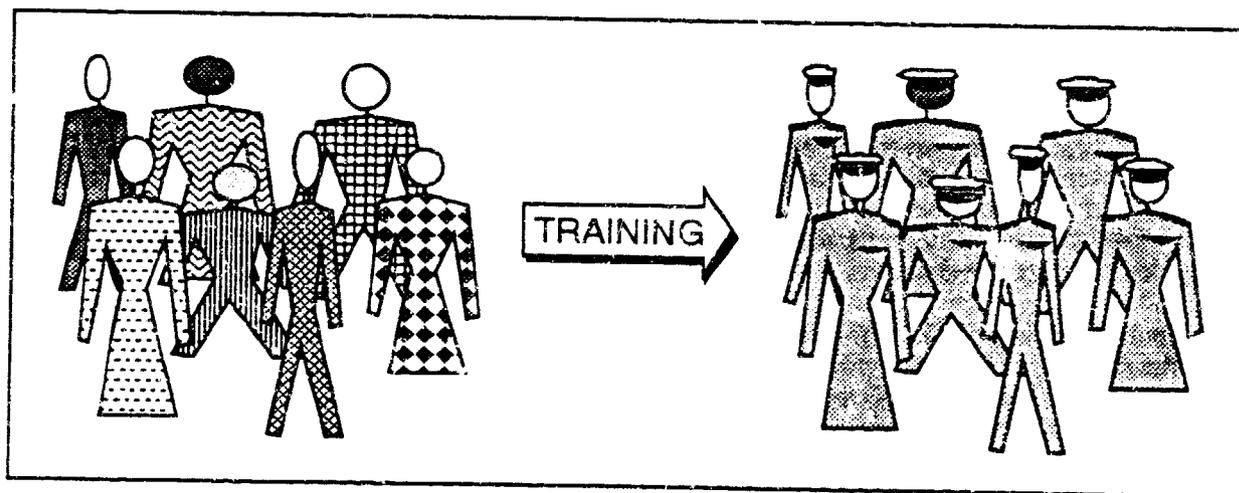


Figure 42: Training is essential for uniformly effective performance.

Training is expensive and time-consuming. Trainees must be paid while in training, time spent in training is lost from production, and a training staff must be maintained. Air carriers have

taken many innovative steps to reduce training time while improving the quality of their training programs; the FAA has recently issued a major revision of its policies regarding training (ref. 93). Nonetheless, a less experienced, more diverse pilot population is now the object of airline training; all students must be brought to airline standards (figure 42). The introduction of advanced automation does *not* reduce training requirements; on the contrary, pilots must now learn to operate very complex automation as well as the other airplane systems. Training managers as well as line pilots have expressed concern about whether training time formerly devoted to improving airmanship is now diverted to training to operate automated systems and about the possible effects of this change in emphasis (refs. 77 and 94).

It is tempting to suggest that advanced automation may be able to permit the selection as air carrier pilots of less qualified persons than have been required heretofore. Indeed, in other industries employing advanced automation (notably the nuclear power industry), operators without advanced education and experience have been the rule. In aviation, however, there has been no tendency thus far to take this approach, and the need for pilots and air traffic controllers to bring intellectual as well as manual skills to their jobs has not lessened. Experimental studies have indicated that the most successful pilots in taxing missions bring to their tasks a high degree both of expressivity (social skills) and instrumentality, or task orientation (ref. 95). One threat posed by advanced automation is that it may make things too simple and may remove from flying the challenges that are the source of much of the ego-gratification and job satisfaction that the profession now offers to pilots, most of whom would still rather be flying for a living than doing anything else.

IV: ATTRIBUTES OF HUMAN-CENTERED AIRCRAFT AUTOMATION

Introduction

In a landmark paper in 1980, Wiener and Curry discussed "Flight-Deck Automation: Promises and Problems" (ref. 35). They pointed out that even at that time, the question was "not whether a function can be automated, but whether it should be, due to the various human factor questions that are raised." They questioned the assumption that automation can eliminate human error. They pointed out failures in the interaction of humans with automation and in automation itself.

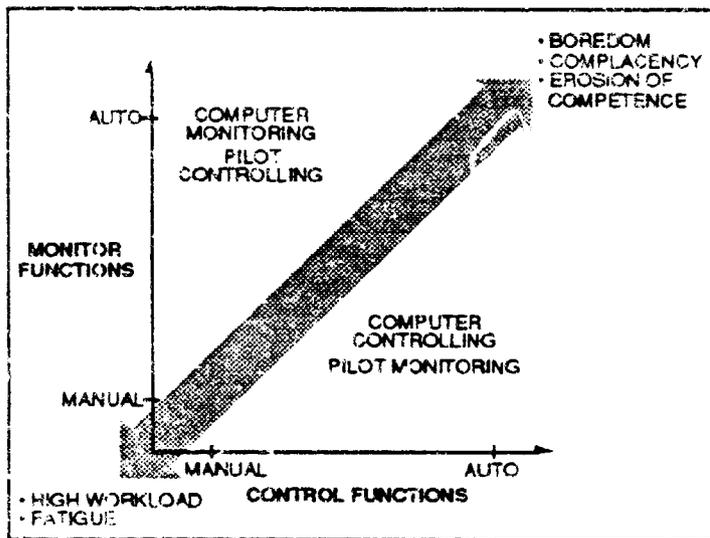


Figure 43: Monitoring and control functions
(redrawn from Wiener and Curry, 1980).

It is worth recalling Wiener and Curry's guidelines, because they foresaw many of the advantages and disadvantages of automation as it is used today. The following are abstracted from their guideline statements.

Control tasks

1. System operation should be easily interpretable 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...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...
3. Design the automation to prevent peak levels of task demand from becoming excessive...keeping task demand at reasonable levels will insure available time for monitoring.
4. ...The operator must be trained and motivated to use automation as an additional resource (i.e., as a helper).

They discussed control and monitoring automation and emphasized the independence of these two forms of automation (figure 43); "it is possible to have various levels of automation in one dimension independent of the other."

The authors then discussed system goals and design philosophies for control and monitoring automation. They suggested some generalizations about advantages and disadvantages of automating human-machine systems, and went on to propose some automation guidelines for the design and use of automated systems in aircraft.

5. Operators should be trained, motivated and evaluated to monitor effectively.
6. If automation reduces task demands to low levels, provide meaningful duties to maintain operator involvement and resistance to distraction...it is extremely important that any additional duties be meaningful (not "make-work")...
7. Allow for different operator "styles" (choice of automation) when feasible.
8. Insure that overall system performance will be insensitive to different options, or styles of operation...
9. Provide a means for checking the setup and information input to automatic systems. Many automatic system failures have been and will continue to be due to setup error, rather than hardware failures. The automatic system itself can check some of the setup, but independent error-checking equipment and procedures should be provided when appropriate.
10. Extensive training is required for operators working with automated equipment, not only to insure proper operation and setup, but to impart a knowledge of correct operation (for anomaly detection) and malfunction procedures (for diagnosis and treatment).

Monitoring tasks

11. Keep false alarm rates within acceptable limits (recognize the behavioral effect of excessive false alarms).
12. Alarms with more than one mode, or more than one condition that can trigger the alarm for a mode, must clearly indicate which condition is responsible for the alarm display.
13. When response time is not critical, most operators will attempt to check the validity of the alarm. Provide information in the proper format so that this validity check can be made quickly and accurately...Also, provide the operator with information and controls to diagnose the automatic system and warning system operation.
14. The format of the alarm should indicate the degree of emergency. Multiple levels of urgency of the same condition may be beneficial.
15. Devise training techniques and possibly training hardware...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.

The authors concluded that "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" (emphasis supplied). Their statement is true today and their call is as appropriate as when it was written. The remainder of this document is devoted to expanding on their guidelines with the benefit of an additional decade of experience and hindsight.

System Goals

Before considering guidelines for aircraft automation, it is wise to remind ourselves of what the aviation system is all about, to consider how and why automation is necessary and beneficial, and to review those aspects of automation that may need improvement.

Wiener and Curry (ref. 35) outlined several system goals from the viewpoint of the user:

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.

We suggest a very similar list as the minimum which must be attained; we feel also that the list must be sufficient from the viewpoints of all involved: the manufacturer, the airline, the pilots, the air traffic management system, and the passenger. Not all (nor indeed any) of these participants will be satisfied with every flight, but all must agree in general with the goals of the system. We believe these are the goals of the air transportation system:

1. **Safety:** To conduct all flights, from pushback to docking, without harm to persons or property.
2. **Reliability:** To provide reliable transportation without interference from weather or other variables.
3. **Economy:** To conduct all flights as economically as possible.
4. **Comfort:** To conduct all flights in a manner that maximizes passenger and crew health and comfort.

These goals may obviously conflict; tradeoffs among them in operations as well as in design are often required.

Safety has always been proclaimed by the aviation industry as its primary objective, even at the expense of the other goals. The Federal Aviation Act of 1958 (ref. 96) required the FAA to control air carrier operations to maintain "the highest level of public safety," but even this term is elusive. Taken literally, it can be read to require that *any* step that may improve safety, no matter how expensive or burdensome, must be implemented. Taking a slightly less extreme approach, the phrase could be interpreted to mean that any step that can be proven to increase safety will be taken. This is fairly close to the approach that has guided the industry in the past, despite occasional unfortunate exceptions. Reliability, economy and comfort have been secondary goals, though they are critical to the survival of this critical element of the national economy.

Has aircraft automation contributed to the fulfillment of these system goals? An examination of air carrier accidents by Lautmann and colleagues (ref. 97) suggests that more highly automated aircraft have had substantially less accidents than earlier aircraft. Ten years after their introduction, the Boeing 757/767 types have been involved in only one fatal mishap (Thailand, 1991, under investigation), a truly remarkable record in view of the propensity of new types to accumulate most of their accident experience during their earliest years of operation. There have been fatal accidents (though a very small number) involving other current-generation aircraft, but Lautmann's finding is probably correct, and it may auger well for the future, when newer aircraft will have replaced the older fleet.

Nonetheless, the same study showed that some air carriers, nations and regions of the world operate considerably more safely than do others. As these other carriers, nations and regions become more prosperous and acquire more advanced-technology aircraft, will their safety records likewise improve dramatically? The infrastructure of aviation in many areas of the world is still sorely lacking, and it takes more than excellent aircraft to make an excellent safety record. Will advanced technology be able to compensate for deficient navigation aids and airports? Can automation itself make the system more error-resistant?

Inertial reference systems and map displays certainly make an aircraft less dependent on properly functioning navigation aids and improve position awareness, the lack of which is still associated with an appreciable number of air carrier accidents. Will such improvements, together with satellite navigation systems, compensate for the greater complexity of advanced automation?

Reliability has been improved; autoland-capable automation has increased the number of flights able to land at destinations obscured by very low visibility, and windshear detection devices will provide warning of serious hazards that may not be apparent to pilots. Collision-avoidance systems will likewise provide additional protection against an increasingly frequent hazard. Will improvements in aircraft automation be able to counteract, to some extent, the delays forced by increasing congestion in the airspace system? Time-based ("four-dimensional," or 4-D) navigation, a probable feature of the next generation of flight management systems, will at least permit us to make most effective use of the fixed volume of airspace.

Economy has been improved by flight management systems that can take costs into account in constructing flight plans, though the benefits possible from such computations have been diluted by the inability of the ATC system to permit aircraft to operate on most cost-efficient profiles. This should be improved by ATC automation during the coming decade, as well as by time-based navigation software in new flight management systems.

Comfort has been improved by gust alleviation algorithms in some of the newest aircraft, as well as by the ability of newer aircraft to fly at higher altitudes; comfort in the cockpit has also been improved by better ergonomic design. Greater flexibility enabled by ATC automation will permit pilots to utilize a wider range of options to achieve more comfortable flight paths.

In what respects are we still deficient with respect to these system goals? It is not the purpose of this document to laud what has already been accomplished, but to examine what can be done to affect further improvement, and in the introduction we suggested that further improvement is clearly possible. Most of our accidents can be traced to the human operators of the system, and some can be traced to the interactions of humans with automated systems. We believe that more can be done to make aircraft automation more human-centered, but perhaps even more important, we believe that advanced automation can be designed and used to make the system as a whole more resistant to and tolerant of human errors in the design, the implementation, and the operation of these systems. Our guidelines accordingly emphasize this aspect of automation, one that we think has received less attention in the past than it deserves.

Attributes of Aircraft Automation

We will discuss here several attributes that human-centered aircraft automation should possess. Our discussion of these attributes may seem anthropocentric, but humans are used to thinking in these terms. If automation is to be an effective and valued member of the cockpit management team, it, like the other members of the team, should possess these characteristics. Each attribute is named, defined, described and discussed briefly. Our first guideline might be simply that human-centered aircraft automation should possess these attributes in proper measure.

The reader of this section must keep in mind that these requirements are not mutually exclusive. An automation suite that possesses some, or even many, of these attributes may still be a failure if they are considered in isolation during design, for several are interrelated. As in any engineering enterprise, it is necessary that the right compromise among them be sought. The only way to be sure that an effective compromise *has* been reached is the evaluation of the total system in actual or simulated operation by a variety of pilots of differing degrees of skill. Such testing is expensive and time-consuming; it must often be conducted late in development, under extreme pressure to certificate and deliver a new aircraft on time. Nevertheless, it is the only way to prove the safety and effectiveness of an automation concept.

We are indebted to Fadden (ref. 98), who has pointed out that many of these attributes are to some extent bipolar, though not truly opposites. That is, increasing the attention to certain attributes may require de-emphasizing others. We will discuss these attributes, shown here in the manner suggested by Fadden. Human-centered automation must be:

<i>Accountable</i>	<—————>	<i>Subordinate</i>
<i>Predictable</i>	<—————>	<i>Adaptable</i>
<i>Comprehensible</i>	<—————>	<i>Flexible</i>
<i>Dependable</i>	<—————>	<i>Informative</i>
<i>Error-resistant</i>	<—————>	<i>Error-tolerant</i>

Accountable means "subject to giving...a justifying analysis or explanation." In older aircraft, automation executed actions only at the specific and immediate instruction of a human crew member. Advanced automation, however, is capable of more independent action (modifying a climb or descent based on pre-determined strategic objectives such as fuel conservation, entering or leaving a holding pattern, resolving a conflict, etc.). Automated decision-aiding or decision-making systems, already in development for transport aircraft, will suggest or carry out courses of action whose rationale may not be obvious to flight crews.

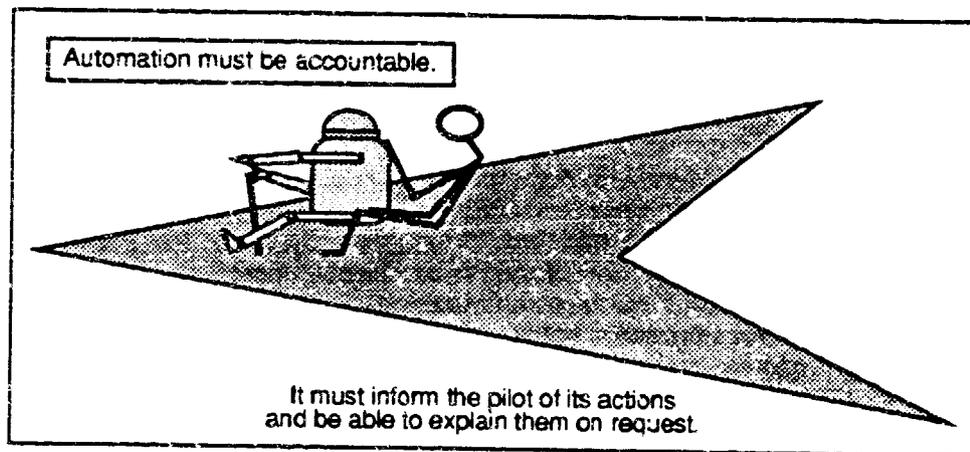


Figure 44: Accountability of automation.

The human in command must be able to request and receive a justification for such decisions (figure 44). This is a particular problem in aviation; there may not be time for the human operator to evaluate such decisions (terrain avoidance, collision avoidance or windshear compensation maneuvers). Where possible, automation must anticipate the pilot's request and provide advance information (as TCAS does by providing traffic advisories prior to requiring action to avoid an imminent hazard) or its rules of operation in a particular, annunciated circumstance must be so thoroughly understood by pilots that its actions in that case are already understood and accepted. It is particularly important that explanations provided by automation be cast in terms that make sense to the pilot; the level of abstraction of such explanations must be appropriate to the pilot's need for the explanation.

The MD-11 aircraft systems controllers take action autonomously when certain failures occur. In these cases, pilots can access information regarding the faults by examining the system synoptics if time permits. They could reverse the actions taken, if necessary, by reverting to manual operation of the reconfigured subsystem, though such action is not encouraged. As more autonomous systems are introduced, however, it may be increasingly difficult for pilots to keep track of what the airplane (or its automation) is doing, and increasingly difficult for them to maintain oversight of all aspects of their operation even if they are informed of each action. The bipolar attribute of accountability is subordination, to be discussed below; great care must be taken to insure that this cannot ever become *insubordination*. The 2001 "Hal" scenario is almost within our grasp technically, but it is not acceptable philosophically as long as human operators remain responsible for the outcome.

Subordinate means "placed in or occupying a lower class, rank or position." Our definition of human-centered automation requires that the automation, while an important tool, remain subordinate to the human pilot or air traffic controller, who must remain in command (figure 45).

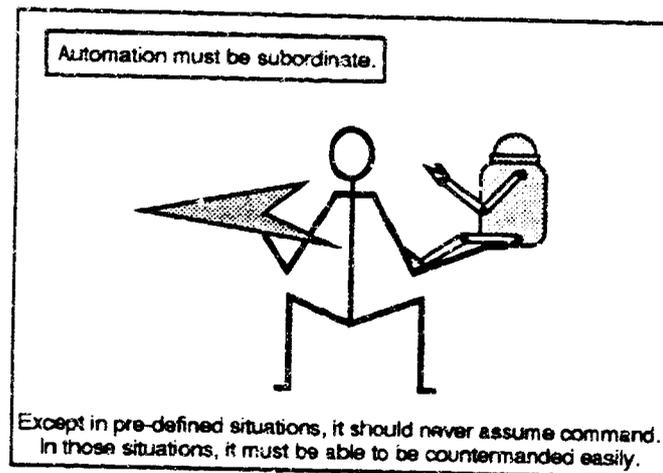


Figure 45: Subordination of automation.

There are situations in which it is accepted that automation should perform tasks autonomously, as indicated above. More such situations will be proposed for implementation in the future; in particular, it is expected that ground proximity, traffic avoidance and windshear advisory systems will be provided with the means to act independently. Other similar situations are likely to be proposed in future, involving the interaction of aircraft and ATC. Should these be permitted?

We have seen cases in which automation acted in ways not expected nor desired by pilots. In one case, aircraft occasionally turned toward the outbound rather than the inbound track of an ILS localizer. In another, a particular automation mode permitted descent at idle thrust without regard to safe minimum operating altitudes. As automation becomes more self-sufficient, capable and complex, it will be increasingly difficult for pilots to remain aware of all actions being taken autonomously and thus increasingly difficult for them to be aware of exactly what the automation is doing and why. Such a situation will tend to compromise the command authority and responsibility of the human operators, but more important, it may lead them to a position of extreme distrust of their automation, which could compromise the integrity of the entire human-machine system. Wiener has reported that pilots of highly automated aircraft frequently ask, "What's it doing now? Why is it doing that?" (ref. 99). These questions should not be necessary.

Predictable is defined as "able to be foretold on the basis of observation or experience." It is an important characteristic; recent occurrences in which automation did not appear to behave predictably, i.e., as expected by pilots, have led to major repercussions due in large part to aviators' inherent distrust of things over which they do not have control. Some of these occurrences are cited above. Here again, the level of abstraction at which automation is explained, or at which it provides explanations, is critical to the establishment and maintenance of trust in it. The third question too often asked by pilots of automated aircraft is "What's it going to do next?"

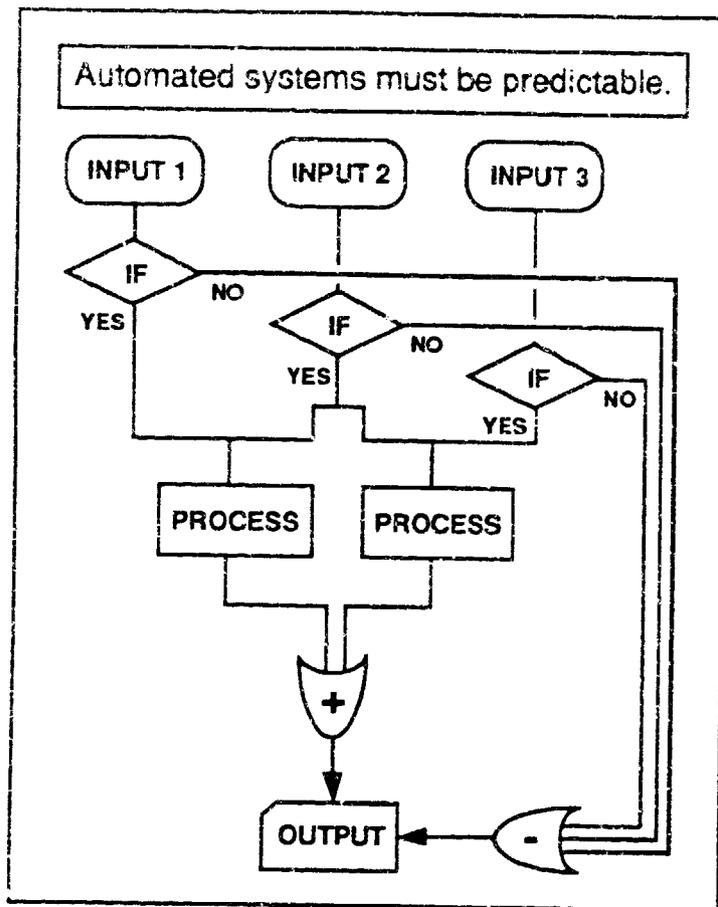


Figure 46: Predictability of automation.

Advanced automation must be designed both to be, and to appear to be, predictable to its human operators (and these are not always the same thing, which is why explanations may be necessary) (figure 46). As noted earlier, when digital computers fail, they may do so in quite unpredictable ways; the difference between these failures and their normal behavior must be immediately apparent to the pilot.

Adaptability (discussed below) and predictability are, in a sense, opposites, in that highly adaptive behavior is liable to be difficult to predict. The behavior of the human organism, which is characterized by a very high degree of adaptability may be difficult to predict (ref. 70), a fact that we constantly try to overcome by training, standard operating procedures, line and proficiency checks and a variety of other safeguards. This suggests the necessity for constraints on the adaptability of automation in a context in which the human must be able to monitor the automation and detect either shortcomings or failures in order to compensate for its inadequate behavior.

As automation becomes more adaptive and intelligent, it will acquire a wider repertoire of behaviors under a wider variety of circumstances. This will make its behavior more difficult for pilots to understand and predict, even though it may be operating in accordance with its design specifications. It will also be more difficult for pilots to detect when it is not operating properly.

If such a system is not predictable, or if it does not provide pilots with sufficient indications of its intentions, its apparently capricious behavior will rapidly erode the trust that the human wishes to place in it. Some automated devices in aircraft have simply gone unused because of this mistrust. Altitude capture modules in some high-performance aircraft have appeared unpredictable because their high rate of approach to a selected altitude has not provided the pilots sufficient confidence that they would stop the airplane's climb at the selected point, even though they were functioning properly—until disabled by the pilots in attempts to slow the rate of climb, which negated the capture function (refs. 62, 100).

Adaptable, as used here, means "capable of being modified according to changing circumstances." This characteristic is already incorporated in aircraft automation: control laws may differ in different speed regimes; certain alerts and warnings are inhibited during takeoff, descent or approach; some displays are reconfigured or de-cluttered in specific circumstances; some information may be unavailable either in flight or on the ground.

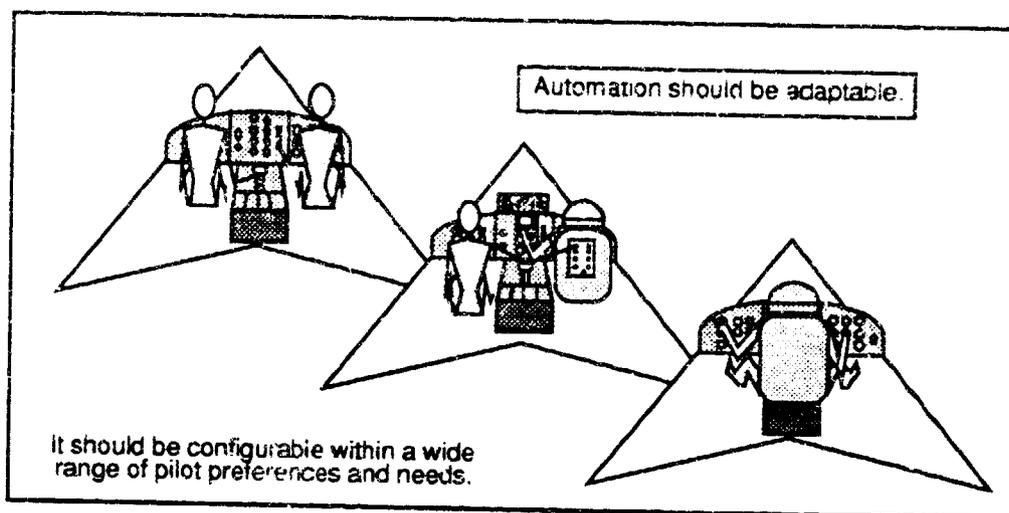


Figure 47: Adaptability of automation.

Pilots need, and are provided with, a range of options for control and management of their aircraft (figure 47). This range of options is necessary to enable pilots to manage their workload, take account of differing levels of proficiency, and compensate for fatigue, distractions or other necessary cockpit activities. In this regard, automation truly acts as an additional member of the control and management team, assisting with or taking over entirely certain functions when instructed to do so.

Adaptability is not an unmixed blessing (nor is any of the other attributes). An incident report received by ASRS in 1976 (ref. 101) described a wide-body aircraft which was turned onto final approach inside the final approach fix with autopilot in control wheel steering mode and autothrottles engaged. During the flare, at 10-20 feet altitude, the airplane seemed to "hang in the air." The pitch angle was very high (14 degrees nose-up) and on touchdown the tail cone and aft fuselage contacted the runway. The autopilot had not been disengaged prior to touchdown, and none of the crew members had noticed that the airplane was still being guided by manual inputs, but in a rate command mode rather than a direct column-to-controls mode. Some air carriers have disabled the autopilot control wheel steering mode in newly-delivered aircraft to lessen the range of options available to flight crews.

How much of a range of options is enough? At this point in time, control automation in some aircraft requires only management by exception. In an earlier section, we have asked whether it would be wiser, in order to maintain pilot involvement at a high level, to require management by consent with respect to control tasks. We have also asked whether the capability for unassisted manual control should be a required option (and have pointed out that this option is foreclosed in some flight phases by at least one flight control system).

Adaptability increases apparent complexity and is shown above contrasted with predictability, to emphasize that extremely adaptable automation may be relatively unpredictable in certain circumstances. One of our first principles of human-centered automation states that automation *must* be predictable, if the human is to remain in command.

Comprehensible is "intelligible." Many critical automation functions are now extremely complex, with several layers of redundancy to insure that they are fault-tolerant. Is it really necessary that the human operator understand how these functions are accomplished, or will simpler models suffice to permit humans to remain in command of the functions (figure 48)?

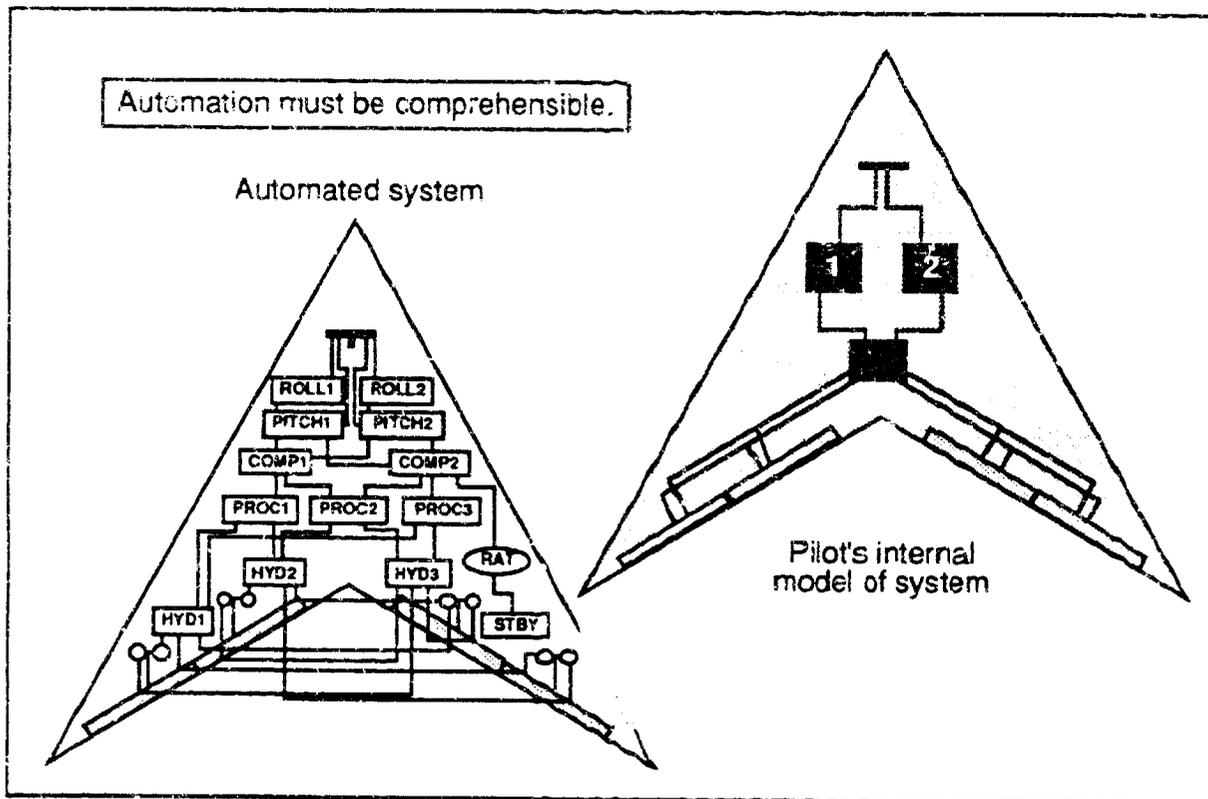


Figure 48: Comprehensibility of automation

It has been noted that training for advanced automated aircraft is time-consuming and expensive, and that much of the extra training time is spent learning about the automation. If simpler models that still permit reversion in the case of failures could be devised, they might result in training benefits. It should be remarked, however, that while automation can be used to make complex functions appear simpler to the pilot, the consequences of failure modes can appear highly unpredictable to that pilot unless the modes are very thoroughly considered in the design phase.

Simplicity has not been named as a necessary attribute for human-centered automation, but it could well have been. It is vital that systems either be simple enough to be understood by human operators, or that a simplified construct be available to and usable by them. If a system is simple enough, it may not need to be automated. If it cannot be made to appear reasonably simple, the likelihood increases that it will be misunderstood and operated incorrectly.

Technological progress is often equated with increased complexity. A careful examination of any reasonably capable video-cassette recorder will support this assertion and indicate how far we have yet to go to make high technology intuitive and simple to operate. It is worth noting that new technology has had to be developed to simplify the operation of VCRs and that many computer manufacturers have provided several "help" levels at which their machines can be operated. We have not provided this range of options in aircraft automation; perhaps we should consider doing so, at least in training.

Flexible is "tractable; characterized by a ready ability to adapt to new, different, or changing requirements." The term is used here to characterize automation that is able to be adapted to a variety of environmental, operational and human variables (figure 49).

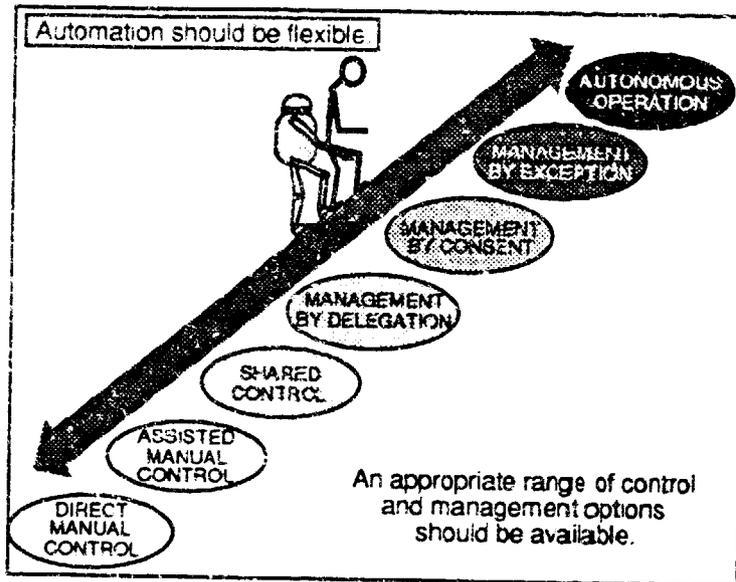


Figure 49: Flexibility of automation.

It was suggested immediately above that computer and software manufacturers have gone to considerable efforts to make their products simple to operate by people of widely differing skill levels. The term used by the trade is "user-friendly." Though overworked, this term denotes a device or application that a wide variety of users can operate comfortably and effectively with comparatively little instruction or practice, surely a worthy aim for any human-machine system but one to which, thus far, too little attention has been paid by avionics designers. It would be desirable to allow pilots to tailor the degree of assistance they wish under given circumstances.

Advanced avionics systems now receive much of their knowledge base from periodic updates by means of disks or cassettes. We believe they could as easily receive information regarding the pilots for a given flight by the same means, and that this information could assist in tailoring the systems and displays both to the preferences of specific pilots and to any limitations under which the pilots are operating at the time (increased minimums, etc.). The cassettes could be updated automatically after each flight to provide a running flight log, types of approaches conducted, etc. If improved monitoring of pilot performance becomes a part of aircraft automation, a subset of monitored data stored on the cassettes after flight might also be of use to flight training departments in tailoring periodic training to individual pilot needs.

This sort of flexibility might be of real assistance both to individual pilots and to companies, by easing the pilot's cockpit setup tasks and also by improving safety through more effective training. It has been observed in military studies that pilots of advanced strike aircraft rarely make use of more than a subset of the available attack modes; by limiting the options that they use, pilots become extremely proficient in their use. Air transport pilots may not need to be proficient in the use of the full range of automation options, as long as they are able to get the job done effectively under both normal and anomalous circumstances. The major reason for having a wide range of automation options is to provide flexibility for a wide range of pilots with experience that varies from very little to a great deal and cognitive styles that vary as widely.

Flexibility was shown above as bipolar with comprehensibility. Given the tendency to an inverse relationship between these variables, comprehensibility must not be sacrificed for flexibility, because the ability of pilots to understand their automation is central to their ability to maintain command. But they can be given more help in understanding it and in manipulating it by the means used in other fields. Providing that help in recognition of differing needs and styles among pilots can help to improve the error resistance of the total system by permitting individual pilots, within the constraints imposed by flight operations, to conduct their tasks in ways that are most comfortable for them.

Dependable, as used here, means "capable of being...relied upon or trusted" (figure 50). In a cooperative human-machine system, the issue of trust becomes paramount. Pilots will not use, or will regard with continual suspicion, any aircraft device or function that does not behave reliably, or that appears to behave capriciously. This distrust can become so ingrained as to nullify the intended purpose of the designer. It may be wiser to omit a function entirely, even a strongly-desired function, rather than to provide or enable it before it can be certified as reliable. This issue came up during initial implementation of GPWS. It has recently surfaced again as a result of a small number of apparently paradoxical resolution advisories provided by TCAS-II, leading some members of the community to suggest that the resolution advisory mode of the system be disabled until its algorithms are made fully dependable under all circumstances.

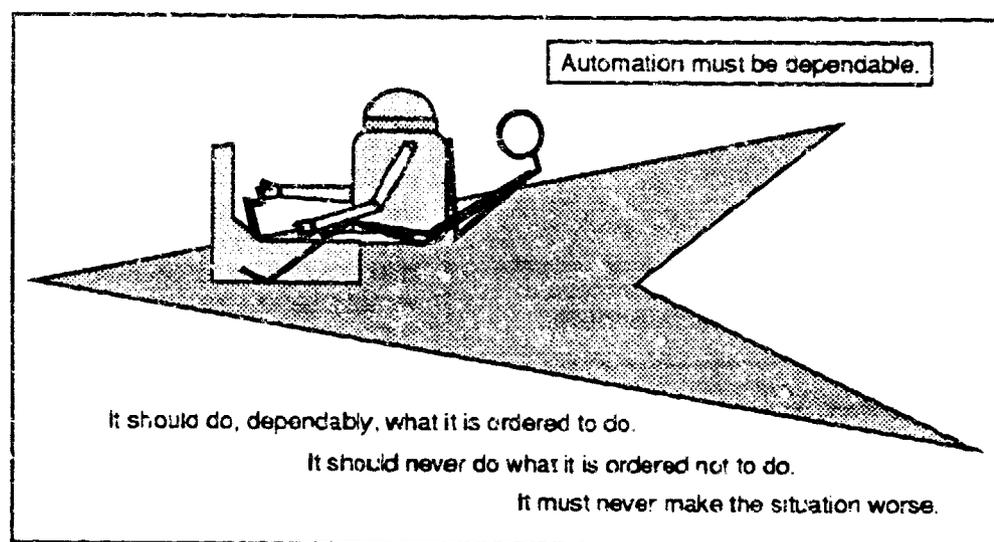


Figure 50: Dependability of automation.

Another example of undependable automation was cited above, that of the localizer capture mechanism which occasionally directed the aircraft to turn away from, rather than toward, the landing runway during the capture process. From the pilot's viewpoint, it makes little difference whether such behavior is caused by the hardware, a software error, or an improperly-defined function; the net effect is a deterioration of trust.

Dependability is of particular importance with respect to alerting and warning systems. We have observed before the problem of "false alarms" with early ground proximity warning systems and the tragic results due to mistrust of legitimate warnings by those systems. Unfortunately, any increase in the sensitivity of such a warning system will be accompanied by an increase in false warnings; a decrease in sensitivity will be accompanied by an increase in failures to warn when a warning is needed. Increasing the complexity of the algorithms to minimize false warnings while increasing sensitivity is accompanied by a decrease in reliability or dependability of the system. This dilemma exists today with regard to TCAS algorithms, already very complex, in the face of large numbers of "nuisance" alerts in certain congested terminal areas.

Dependability is shown as bipolar with informativeness, discussed immediately below. If a system were perfectly dependable in operation, there might be no need to inform the pilot of its operation. Perfection is impossible to achieve, however, and the information provided must be as nearly foolproof as possible, bearing in mind that each increase in information quantity makes it more likely that the information may be missed, or even incorrect. Simplicity of systems breeds dependability; when faced with a dilemma such as this, any system simplification that can be achieved will probably pay dividends.

Informativeness is simply the condition of "imparting knowledge." Our first principles of human-centered automation state that the pilot must always have basic information (figure 51).

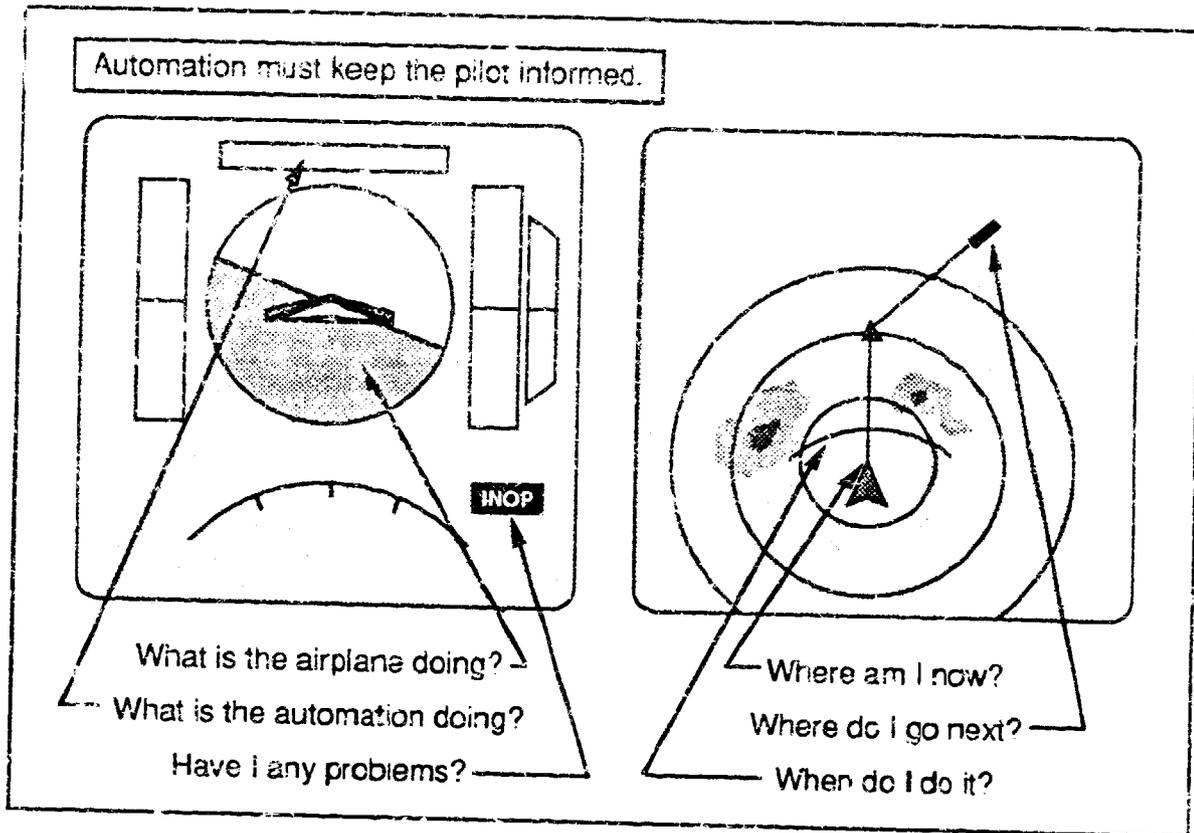


Figure 51: Informativeness of automation.

As was noted earlier, the flexibility of automation and display technology have permitted the designer wide latitude in providing new graphic information in the cockpit. It was also noted that new displays have proliferated, and that this is not an unmixed blessing. The pilots of the A320 aircraft which contacted the ground at Bangalore (ref. 13) failed to notice, among other things, serious decay in airspeed during the approach. The pilots of the 737 that crashed on takeoff at LaGuardia did not detect that the rudder trim was in an extreme position (ref. 89). Of course, pilots of older aircraft have also failed to detect incorrect configurations whose presence was clearly visible in the cockpit, and the flight crew of the China Air 747 over the Pacific failed to detect several indications, all clearly visible, that their autopilot was working at its limits following an engine failure (ref. 14).

How much information is enough? How much information is too much? Pilots want all they can get, but they cannot assimilate too much, and what they will leave out is unpredictable. In an effort to make available as much information as is desired, we may have provided too much information — or we may simply not have done it well enough. This is our reason for suggesting (pp. 43-47) the desirability of de-clutter, simplified displays and format changes: in short, of active as opposed to passive information management, to assist the pilot in prioritizing information transfer to insure that the most important things are attended to first. Once again, problems may arise because of automation itself, or simply because the interfaces between the automation and the human are not optimal. Information is critical both for involvement in the task and for maintaining command over it. The form of that information will often determine whether it can be attended to or not. Some level of active information management is practiced now (non-essential information suppression during critical flight phases); a small amount more might convey additional benefits.

Error resistance: Ideally, aircraft automation should prevent the occurrence of all errors, its own and those of the human operators. This is unrealistic, but it is possible to design systems to be as error-resistant as possible, both with respect to their own errors and those of the operator. Resistance is "an opposing or retarding force," a definition that recognizes the relative nature of the phenomenon. Resistance to error in automation itself involves internal testing to determine that the system is operating within its design and software guidelines. Resistance to human error is more subtle, it may involve comparison of human actions with a template of permitted actions, a software proscription against certain forbidden actions under specified conditions, or simply clear, uncomplicated displays and simple, intuitive procedures to minimize the likelihood of errors.

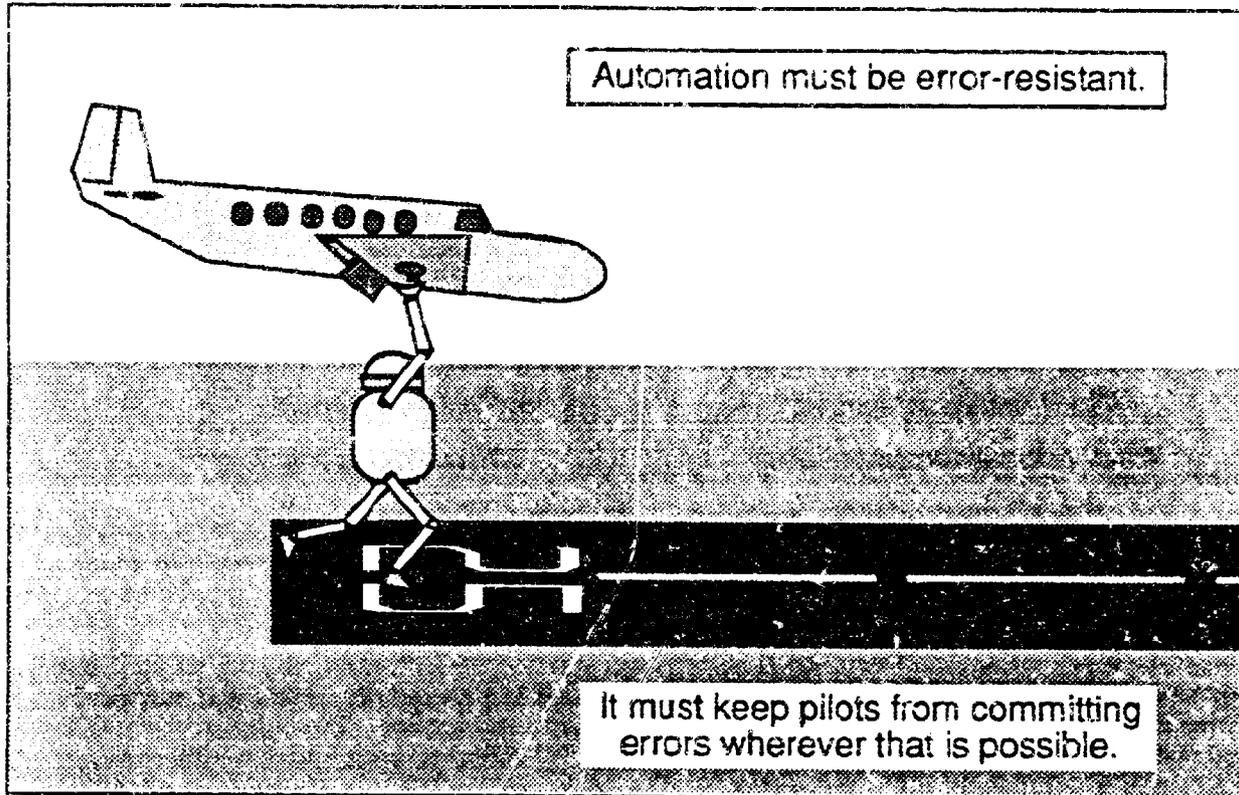


Figure 52: Error resistance of automation.

Automation of unavoidably complex procedures (such as fuel sequencing and transfer among a large number of widely-separated tanks to maintain an optimal center of gravity) is necessary and entirely appropriate provided the human is "kept in the loop" so he or she understands what is going on. The system must be able to be operated by the human if the automation fails, and it must provide unambiguous indication that it is functioning properly. Guidance in performing complex tasks (and fuel balancing may be such a task) is helpful, whether it is in a quick reference handbook or in the form of an electronic checklist. Prompting has not been used as effectively as it could be in aircraft human-system interfaces.

Questioning of critical procedures (those that irreversibly alter aircraft capabilities), or requiring that critical orders be affirmed by pilots before they are executed, can be additional safeguards against errors. These queries can also be automated, either by themselves or as part of a procedures monitoring module which compares human actions with a model of predicted actions under various circumstances. Such models have been developed in research settings (ref. 102).

The human operator is known to commit apparently random, unpredictable errors with some frequency (refs. 70 and 103); it is extremely unlikely that designers will ever be able to devise automation that will trap all of them. This being the case, it is essential to provide alternate means by which pilots can detect the fact that a human, or an automation, error has occurred. Such warnings must be provided in enough time to permit pilots to isolate the error, and a means must be provided by which to correct the error once it is found. Where this is not possible, the consequences of an action must be queried before the action itself is allowed to proceed.

Error-tolerance: Since error-resistance is relative rather than absolute, there needs to be a "layered defense" against human errors. Beside building systems to resist errors as much as possible, it is necessary and highly desirable to make systems tolerant of error. *Tolerance* means "the act of allowing something"; in this case, it covers the entire panoply of means that can be used to insure that when an error is committed, it is not allowed to jeopardize safety.

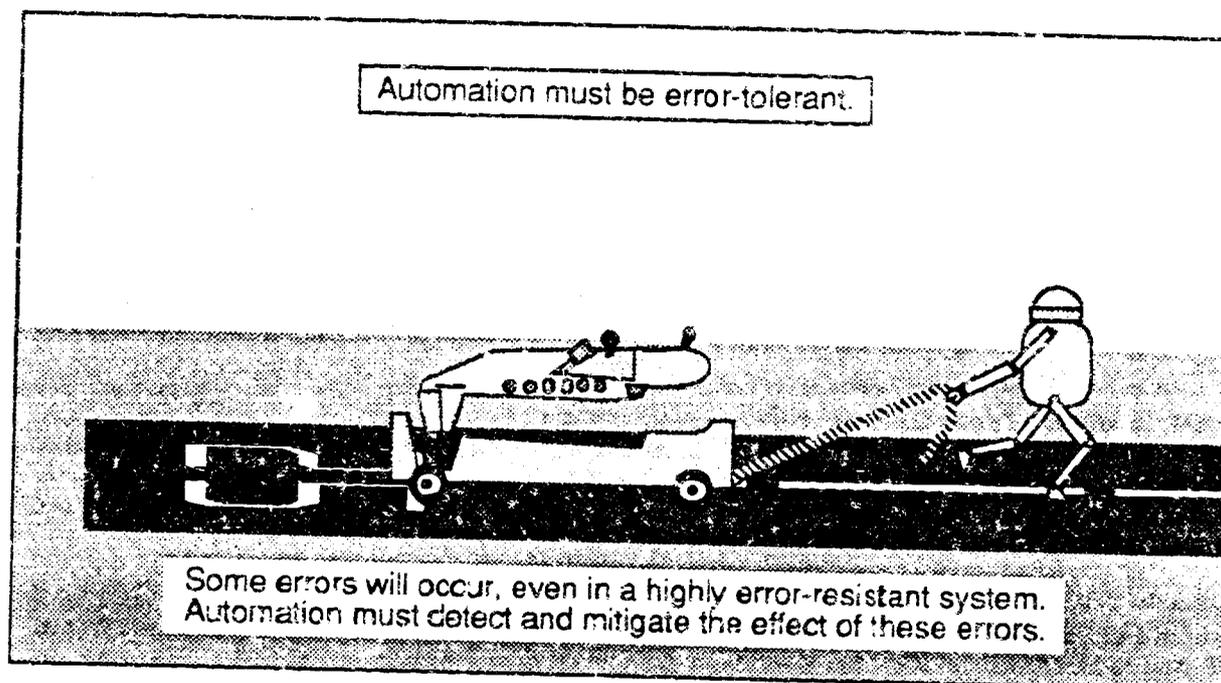


Figure 53: Error tolerance of automation.

Nagel (ref. 42) has pointed out that "it is explicitly accepted that errors will occur; automation is used to monitor the human crew and to detect errors as they are made." The aviation system is already highly tolerant of errors, largely by virtue of monitoring by other crew members and by air traffic control. But certain errors possible with automated equipment become obvious only long after they are committed, such as data entry errors during FMS programming. New monitoring software, displays and devices may be required to trap these more covert errors.

As was suggested above, checks of actions against reasonableness criteria may be appropriate; for an aircraft in the eastern hemisphere, a west longitude waypoint between two east longitude entries is probably not appropriate. An attempted manual depressurization of an aircraft cabin could be an appropriate maneuver to rid the cabin of smoke, but it is more probably an error and should be confirmed before execution. Closing fuel valves on both engines of a twin-engine transport, an action that has occurred at least twice, is almost certainly an error if airborne (ref. 52).

Given that it is impossible either to prevent or to trap all possible human errors, aircraft accident and especially incident data can be extremely useful in pointing out the kinds of errors that occur with some frequency. System hazard analyses are appropriate to elucidate the most serious

possible errors, those that could pose an imminent threat to safety. The latter should be guarded against regardless of their reported frequency. (See also Rouse, reference 20.)

Discussion of Attributes

Error resistance and error tolerance are not opposites, as might be inferred from the bipolar scale shown at the beginning of this section; on the contrary, they are complementary in every respect. Both are highly desirable and necessary; many aspects of automation today incorporate both, though considerable further improvement is possible. The other attributes are more nearly bipolar, and a balance must be struck among them.

The attributes we have suggested are not mutually exclusive; there is overlap among them. Our first principles suggest a rough prioritization where compromises are necessary. We have stated that if humans are to be in command, they must be informed. Accountability is an important facet of informing the human operator, as well as an important means by which the operator can monitor the functioning of the automation. Comprehensibility is another critical trait if the human is to remain informed; he or she must be able to understand without ambiguity what the automation is doing. Each of these traits is an aspect of informativeness.

Informativeness may be interpreted to imply a system that provides information beyond the minimum necessary to operate or manage the equipment, though we do not intend this implication. Rather, it is necessary that the human operator be informed *effectively* of at least that minimum of information at all times, and informed in such a way that there is a very high probability that the information will be assimilated. In those cases where it may not be entirely clear *why* a system is in a particular state, an explanation should be readily available if it is not already known or fairly obvious.

It can be argued that system dependability is degraded by the addition of more information. Though this can be countered in part by adding redundancy and error-checking, the predictability and comprehensibility of the system may be degraded thereby. On the other hand, we know how to produce highly fault-tolerant flight control systems; are highly reliable, fault-tolerant information systems any less important? (See also page 95.)

It may be considered that adaptability and flexibility are frills rather than necessities. To argue this is to argue that humans can be made to behave uniformly, and to a considerable extent this is indeed true, as demonstrated by the enormous success of the air transport industry. The costs of producing inflexible systems, however, are considerable increases in training costs to produce that uniformity in the humans who operate them, and a possible decrease in human operator initiative, a risky enterprise in an industry that requires a high degree of human cognitive flexibility.

The question of subordination has not loomed large until very recently and it should not be contentious today, given that humans bear the ultimate responsibility for the safety of flight operations. Despite this assertion, which is agreed to by regulators and the public alike, it is thought that the degree of independence of automation may be a major battle ground during the coming decade, as the ground element of the air transportation system is automated. We argue simply that automation that bypasses the human operators will of necessity diminish their involvement in and their ability to command the aviation system, which in turn will diminish their ability to recover from failures or compensate for inadequacies in the automated subsystems. That such inadequacies will not exist or that such failures will not occur must be proven conclusively by automation designers before the aviation community can consider an alternative view.

So a balance must be struck; where compromises are necessary, they must err on the side of keeping the human operator in the loop so that he or she will be there when needed. This will be far easier if he or she is there all the time: if the pilot is helped to remain actively involved in normal as well as abnormal operations. Exactly the same statement can be made about the air traffic controller, of course, and about the desirability, if not the necessity, of maintaining and using voice channels of communication between them so that each can remain cognizant of the other's intentions.

V. GUIDELINES FOR HUMAN-CENTERED AIRCRAFT AUTOMATION

Introduction

Having come this far, are there firm requirements that can be applied to all human-centered aircraft automation? We believe there are, though their "firmness" must be tempered by the imperfect state of our knowledge of human behavior, by the compromises that are inevitable in the design process, and by the constraints inherent in the aircraft certification process. In this final section, we will set forth certain guidelines that we believe flow from our review of past and present automation and our best guesses as to the future of this technology.

It is necessary to remind the reader again that no attempt has been made to cover the engineering aspects of human factors in this document. In accordance with the call of the Air Transport Association, we have attempted to construct a philosophy of human-centered automation. One definition of philosophy is "the pursuit of wisdom," and while we may be pursuing it at some considerable distance, we hope our results will further the dialogue we have attempted to provoke.

Principles of Human-Centered Automation—General Guidelines

First, however, we still believe that the principles of human-centered automation set forth briefly in section I constitute a reasonable foundation upon which to build. We therefore repeat them here as general guidelines, with some further discussion of each of them. (Page numbers in parentheses refer to discussions in this document, WC numbers refer to the Wiener and Curry guidelines on pages 66 and 67.)

- *The human operator must be in command.*

In its discussion of AERA 2, the automated en route air traffic control system of the future, MITRE Corporation stated unequivocally that even when the automated system is in full operation, "Responsibility for safe operation of an aircraft remains with the pilot in command," and "Responsibility for separation between controlled aircraft remains with the controller." *Command* is "power to control or dominate by position; authority to command." We believe that if they are to retain the *responsibility* for safe operation or separation of aircraft, pilots and controllers must retain the *authority* to command those operations. Further, there appears to be no appreciable argument concerning this point. The issues relate to whether pilots and controllers will have the authority necessary to execute the responsibilities.

It is a fundamental tenet of our concept of human-centered automation that aircraft (and ATC) automation exists to assist pilots (and controllers) in carrying out their responsibilities as stated above. Our reasoning is simple. Apart from the statutory responsibility of the human operators of the system, automation is not infallible; like any other machine, it is subject to failure. Further, digital devices fail unpredictably, and produce unpredictable manifestations of failures. The human's responsibilities include detecting such failures, correcting their manifestations, and continuing the operation safely until the automated systems can resume their normal functions.

Since automation cannot be made failure-proof, automation must not be designed in such a way that it can subvert the exercise of the human operator's responsibilities, from which it follows that automation must not be used to configure the airplane or load the system beyond human capacity to control and manage it if the automation fails. For a contrary concept, see the quotations from the MITRE report on page 57, which present a considerably different view of air traffic control automation. (See pp. 7, 12, 57.)

- *To command effectively, the human operator must be involved.*

To exercise effective command of a vehicle or operation, the commander must be involved in the operation. *Involved* is "to be drawn in"; the commander must have an active role, whether that role is to control the aircraft (or traffic) directly, or to manage the human and/or machine resources to which control has been delegated. The pilot's involvement, however, must be consistent with his or her command responsibilities; the priorities of the piloting tasks remain inflexible, and the pilot cannot be allowed to become preoccupied by a welter of detail. Automation can assist by providing appropriate information.

Modern aircraft automation is extremely capable; it has made it possible for the aircraft commander to delegate nearly all tactical control of an operation to the machine. We believe that at least some of the aircraft mishaps cited herein can be traced at least in part to the human operators being too remote from the details of machine operation; the China Air 747 mishap near San Francisco is one example. We suggest that human-centered aircraft automation must be designed, and operated, in such a way that it does not permit the human operator to become too remote from operational details, by requiring of that operator meaningful and relevant tasks throughout the conduct of a flight. (See pp. 28,30, WC 6.)

- *To be involved, the human operator must be informed.*

Without information concerning the conduct of an operation, involvement becomes unpredictable and decisions, if they are made, approach randomness. We have suggested what we believe to be the minimum amount of information necessary to apprise the commander of the progress of a flight operation. The level of detail provided to the pilot may vary, but certain information elements cannot be absent if the pilot is to remain involved, and more important, is to remain able to resume direct control of the aircraft and operation in the event of automation failures.

On the other hand, too much information concerning the conduct of the operation can be at least as dangerous as too little. Both the content of the information made available and the ways in which it is presented must reinforce the essential priorities of the piloting task; in particular, situation awareness must be supported and reinforced at all times. (See pp. 14, 16, WC 13.)

In automated aircraft, one essential information element is information concerning the automation. Just as the pilot must be alert for performance decrements or incapacity in other human crew members, he or she must be alert for such decrements in automated systems that are assisting in the conduct of the operation. This leads to the requirement that:

- *The human operator must be able to monitor the automated systems.*

The essence of command of automated systems is the selection and use of appropriate means to accomplish an objective. The pilot must be able, from information about the systems, to determine that system performance is, and in all likelihood will continue to be, appropriate to the flight situation.

To *monitor*, or "keep track of," automated systems, the human must have access to data concerning the functionality both of the hardware in those systems and of the software that instructs them. Because of the difficulty of verifying software while it is functioning, most flight-critical automation involves either duplicate (or triplicate), or dissimilar software performing the same task in different processors, usually with a comparison module that indicates any differences in the results of the calculations performed by the two units. Some triplex systems conduct continuous "voting" to insure continued function; anomalous results in one processor lead to its exclusion from the operating system.

In most aircraft systems to date, the human operator is informed only if there is a discrepancy between or among the units responsible for a particular function, or a failure of those units sufficient to disrupt or disable the performance of the function. In those cases, the operator is usually instructed to take over control of that function. To be able to do so without delay, it is necessary that the human operator be provided with information concerning the operations to date if these are not evident from the behavior of the airplane or system controlled. It is thus necessary that the pilot be aware both of the function (or dysfunction) of the automated system, and of the results of its labors, on an ongoing basis, if the pilot is to understand why complex automated systems are doing what they are doing. (See pp. 23, 24, 31, WC 1, 5, 9, 10.)

- *Automated systems must be predictable.*

To know what automation to use (or not to use), the pilot must be able to predict how the airplane will be affected by that automation, not only at the time of selection but throughout the flight. This task requires that the intent of the automated system be known and that the system be proven by experience to perform in a consistent manner. It is most important that not only the nominal behavior, but also the range of allowable behaviors, be known; all unpredicted system behavior must be treated as aberrant behavior.

If pilots must monitor automation against the likelihood of failures, as we assert they must, they must be able to recognize such failures, either by means of specific warnings or by observation of aberrant behavior by the automated systems. Both are probably desirable for critical systems, to improve detection probability. To recognize aberrant behavior, the pilot must know exactly what to expect of the automation when it is performing correctly.

This requires that the normal behavior of automated systems be predictable and that the pilot be able to observe the results of their operation. It also argues strongly for simplicity in the behavior of such systems, and suggests, as did Wiener and Curry, that automated systems should perform their tasks in the ways that pilots expect them to, in order to make performance failures more obvious. (See pp. 72-73, 76, WC 2, 8, 10.)

- *The automated systems must also be able to monitor the human operator.*

Because human operators are prone to errors, it is necessary that error detection, diagnosis and correction be integral parts of the aviation system. Much effort has gone into making all critical elements of the aviation system redundant, though new technology is still required for certain aspects of this task (independent landing and takeoff monitors are examples). Pilots monitor air traffic controllers, who in turn monitor pilots, as an important instance.

Automated devices perform a variety of monitoring tasks in aircraft, as indicated throughout this document. Incident reports confirm their effectiveness in preventing mishaps. It is also indisputable, however, that failures of such automation have enabled serious mishaps when the automation did not warn that it was disabled and pilots, perhaps made complacent by its effective functioning over a long period, failed to detect the conditions it was designed to detect. Designing warning systems to detect failures of warning systems can be an endless chain, but it is necessary that we recognize the human tendency to rely upon reliable assistants and consider how much additional redundancy is required in essential alerting systems.

We also believe that information now resident in flight management and other aircraft computers can be used to monitor pilots more comprehensively and effectively, if specific attention is given to the monitoring function. We have mentioned the substantial number of non-obvious navigation data entry errors, some of which have had serious effects long after

they were committed. This would seem to be a productive area for error-detection modules, and there are several others which are mentioned herein. Research should be conducted using accident and incident data to determine other areas in which errors are common or have particularly hazardous implications, and ways should be devised to detect such errors and alert pilots to their presence.

The most difficult task, of course, is to monitor pilot cognitive performance and decision making. When a pilot consciously decides to do nothing, his decision cannot be differentiated from a failure to do something. Further, advanced automation has made the need for decisions and actions infrequent during cruising flight. The advent of extremely long haul aircraft has emphasized the problem of monitoring human alertness and functionality. This is the motivation for our emphasis on keeping pilots involved in a meaningful way in the operation.

There is no way to make the system totally foolproof, and each additional piece of hardware or software has a potential decremental effect on system reliability, but as we pointed out in our discussions of error resistance and error tolerance, a layered defense against errors is essential if we are to make the system as foolproof as possible. (See pp. 32, 78-79, WC 9.)

- *Each element of the system must have knowledge of the others' intent.*

Cross-monitoring (of machine by human, of human by machine and ultimately of human by human) can only be effective if the agent monitoring understands what the monitored agent is trying to accomplish, and in some cases, why. The intentions of both the automated systems and the human operators must be known *and communicated*; this applies equally to the monitoring of automated systems by pilots, of aircraft by human controllers on the ground, and of air traffic control by human pilots in flight. Since humans are so much more versatile than any machine, ultimate responsibility for monitoring of human behavior rests upon the other humans in the system.

Under normal circumstances, pilots communicate their intent to ATC by filing a flight plan, and to their FMS by inserting it into the computer or calling it up from the navigation data base. ATC, in turn, communicates its intent to the pilots by granting a clearance to proceed; data link in the near future will make this information available to the FMS as well. The MITRE document referred to above mentions specifically that "Information on aircraft flight intent can be sent from aircraft to the ATC system so that conflict prediction and resolution capabilities of AERA use the best data available" (ref. 80). The document is silent with respect to communication of intent in the other direction, however, and such communication must be a two-way channel.

It is when circumstances become abnormal, due either to environmental problems or to in-flight emergencies, that communication of intent among the various human and machine agents becomes less certain. ASRS and other data provide evidence of the frequency with which the handling of an in-flight emergency may lead to other anomalies in the system, most commonly involving aircraft other than those involved in the emergency. In one study, the handling of in-flight emergencies led in approximately one-third of cases to another problem (ref. 85).

It cannot be stated with certainty from the ASRS data that communication of intent would have averted these secondary problems, but it seems likely that it would have prevented some of them. Further, the communication of intent makes it possible for all involved parties to work cooperatively to solve the problem. Many traffic control problems occur simply because pilots do not understand what the controller is trying to accomplish, and the converse is also true. Finally, automation (or ATC) cannot monitor pilot performance effectively unless it

understands the pilot's intent, and this is most important when the operation departs from normality. (See pp. 28, 55, 56, 72, 80.)

To the principles set forth above, we will add a few other guidelines of a general nature which have emerged from our review of automation.

- *Functions should be automated only if there is a good reason for doing so.*

To quote from Wiener and Curry (ref. 35), "Any task can be automated. The question is whether it should be..." Would automating a new function improve pilot capabilities or awareness? Would *not* doing so improve the pilot's involvement, situation awareness, or ability to remain in command? We believe that both of these questions should be asked prior to the consideration of any new element of automation in the cockpit. (See pp. 4, 10, 31-32.)

- *Automation should be designed to be simple to train, to learn, and to operate.*

We believe that aircraft automation to date has not always been designed to be operated under difficult conditions in an unfavorable environment by tired and distracted pilots of below-average ability. Yet these are precisely the conditions where its assistance may be most needed. We urge that simplicity, clarity and intuitiveness be among the cornerstones of automation design, for they will make it a better and more effective tool. Though training, strictly speaking, is not the province of the designer, training must be considered during the design of cockpit systems and should reflect that design in practice. (See pp. 11, 25, 35, 39, 60, 63-65, 74, 78-79, WC 5, 10, 15.)

Guidelines for Human-Centered Control Automation

Based on our review of aircraft automation, and drawing heavily upon the guidelines set forth by Wiener and Curry a decade ago, we propose some more specific guidelines for human-centered automation. We first consider control automation.

- *Control automation should perform tasks in a manner familiar to and used by pilots; it should never be permitted to fail silently.*

Wiener and Curry set forth the dictum that automation should behave the way pilots do (WC 2). There are two advantages to this. First, pilots will be more likely to accept and utilize automation that behaves in a familiar manner. Second, and perhaps more important, they will be more likely to recognize a departure from such performance if the automation continues to perform, but in an aberrant manner. Particularly with fault-tolerant control automation, partial or incipient failures may be very difficult to detect because system behavior usually does not change. Whether such partial failures should be announced in order to keep the pilot informed also needs to be considered; it may depend on how much functional redundancy remains in the automated system.

"Fail-passive" control automation represents a particular potential hazard, in that its failure may not change aircraft performance at the time if the airplane is in a stable condition. Such failures must be announced unambiguously to insure that the pilots immediately resume active control of the machine. Automation should never permit a situation in which "no one is in charge"; pilots must always "aviate," even if they have delegated control to the autopilot. It is for this reason that autopilot disconnects are usually announced by both visual and aural alerting signals. (See pp. 4, 19, 24, 71-72, WC 1, 2, 8.)

- ***Control automation should be delimited in its authority. It should not be permitted to become insubordinate.***

Control automation should not be able to endanger an aircraft or to make a difficult situation worse. It should not be able to cause an overspeed, a stall, or contact with the ground without explicit instructions from the pilot, and possibly not then. If the pilot approaches safe operating limits, the automation should warn the pilot, giving him or her time to recognize the problem and take corrective action.

Some current electronic engine controllers withdraw engine power to flight idle autonomously if an overspeed is detected, without regard to whether other engines are operating. This feature cannot be locked out at present. We would argue that this is potentially insubordinate automation.

The pilot should not be permitted to select a potentially unsafe automatic operating mode; automation should either foreclose the use of such modes or should alert the pilot that they may be hazardous, and why. (See pp. 30, 71, 80, WC 4.)

- ***Do not foreclose pilot authority to override normal aircraft operating limits when required for safe mission completion without truly compelling reasons for doing so.***

Limitations on pilot authority may leave the pilot unable to fulfill his or her responsibility for safety of flight. A recent ASRS incident report, one of many, underscores the need to preserve pilot capability to do what is necessary: an abrupt 50° banked turn was required for collision avoidance in an advanced technology wide-body airplane (ref. 104). There have been several cases in which pilots have violated legal G limits; in nearly all of these, the aircraft have been recovered, though with damage. These maneuvers would not have been possible had hard envelope limits been incorporated. We suggest that the "soft limits" approach represents a way to avoid limiting pilot authority while enhancing flight safety. (See pp. 21, 29-30, 39-40, WC 7.)

- ***Design control automation to be of most help during times of highest workload, and somewhat less help during times of lowest workload.***

Field studies of aircraft automation have suggested that it may appreciably lighten workload at times when it is already low, while imposing additional workload during times when it is already high, during climbs and particularly descents. While much of the additional burden relates to problems in interacting with the flight management system (see below), the end product of that interaction is the control and guidance of the airplane as it moves toward its destination.

Avionics manufacturers have made appreciable strides in easing this workload by providing lists of arrival and runway options at particular destinations, but air traffic control at busy terminals may utilize procedures that differ from those listed. In particular, "sidestep" maneuvers to alternate parallel or converging runways are a problem in this regard, especially if clearances are altered late in a descent. Easing such problems may require a better understanding by ATC of what is, and is not, reasonable to ask of a highly automated airplane. Given the congestion at our busiest terminals, however, ATC is likely to continue to seek more, rather than less, flexibility and any short-term improvements will have to be in the cockpit (see also management automation guidelines).

During cruise flight at altitude, the maintenance of pilot involvement is important (see above). Workload may be very low and should quite possibly be increased during long flight segments. (See pp. 17, 28, 47, WC 3, 6.)

- *Keep the flight crew involved in the operation by requiring of them meaningful and relevant tasks, regardless of the level of management being utilized by them.*

High levels of strategic management have the potential to decrease pilot involvement beyond desirable limits. Control automation should not permit this degree of detachment, lest the pilots be unable to reenter the loop in the event of its failure. Keeping pilots involved may require less automation rather than more, but involvement is critical to their ability to remain in command of an operation.

Much critical flight data is now accessed from lookup tables in aircraft performance data bases resident within the FMS. (Critical speeds for approach and landing are examples.) If it is necessary to be more certain that pilots are aware of these data, the designer may wish to consider requiring that the data be either entered manually, or verified by the pilots, before use. The latter option takes less time, but may be less effective.

We have suggested that requiring management by consent rather than management by exception may be one way to maintain involvement, though it has also been pointed out that we do not yet know how to keep consent from becoming perfunctory, and this must also be avoided. One way to assist may be to give more attention to workload management, as is suggested in the preceding guideline. (See pp. 28-29, 65, 94, WC 6.)

- *Control automation should be designed for maximum error resistance and error tolerance.*

Both automated control systems and their associated displays should be made as error resistant as is feasible by designing clear, simple displays and unambiguous responses to commands. Thereafter, safety hazard analyses should be performed to elucidate remaining points at which errors can be committed. The designs should then be modified to incorporate the highest possible degree of error tolerance as well, by proscribing potentially hazardous instructions or by providing unambiguous warning of potential consequences that can ensue from an instruction. Accident and incident data should be reviewed on an ongoing basis to identify likely human and machine deficiencies and these deficiencies should receive special attention in this process.

Human errors, some enabled by equipment design, bring more aircraft to grief than any other factor. Error resistant systems can protect against many of these errors, but it is necessary to give pilots authority to act contrary to normal operating practices when necessary and this requires that designs also incorporate error tolerance. (See pp. 24, 56, 78-79, WC 1, 9.)

- *Control automation should provide the human operator with an appropriate range of control and management options.*

The control and management of an airplane must be safely accomplished by pilots whose abilities vary, under circumstances that vary widely. To provide effective assistance to whomever is flying, under whatever conditions, a degree of flexibility is required in aircraft automation. The aircraft control-management continuum has been discussed; problems at the extremes of this continuum have been indicated (high workload at the low end of the spectrum, possible decreased involvement at the high end of the spectrum). The range of control and management options appropriate to a given airplane must be wide enough to encompass the full range of pilots who may operate it, under the full range of operating conditions for which it is certificated. (See pp. 26-29, 73, WC 7, 8.)

Guidelines for Human-Centered Information Automation

It will have been noted that some of the guidelines above relate to information provided to the pilots as well as to the control of the airplane and its subsystems. It is not always possible to draw a clear distinction between control and information automation, for all automation involves the requirement to keep pilots informed. The following are suggested guidelines specifically for information automation.

- *The primary objective of information automation is to maintain and enhance situation awareness. All displays should contribute to this objective.*

We have indicated (p. 77) what we believe are the minimum elements of information required by pilots at all times. Many other information elements are also required in some form, however (p. 16). The question is not whether these are needed, but in what form they will best reinforce the pilot's awareness of his or her situation and state. The remaining guidelines in this section address this issue in general terms. (See pp. 23-24, 35, 42, 43, 63.)

- *Assume that pilots will rely on reliable automation, because they will.*

Once pilots have flown an automated airplane long enough to become comfortable with it, they will come to know which control and information elements can be trusted. Thereafter, most (though not all) pilots will become increasingly reliant upon the continued reliability of those elements and therefore less liable to be suspicious of them if they become unreliable. For that reason, the designer must not make flight-critical information available unless it is reliable (and must also provide the pilot with information concerning the status of the automation as well as of the element controlled by that automation).

If information is derived or processed, the designer must insure that the data from which it is derived is also either visible or accessible for verification. If it is not critical information for a particular flight phase, make it available only on request, but insure that it remains accessible.

Future automated decision support systems may pose a serious problem in this regard, if pilots come over time to rely on the quality of the machine decisions. A poor decision may be much more difficult to detect than an aberrant subsystem operation. (See pp. 4, 37, 38-39, 48, 76, 95, WC 15.)

- *Automated systems must be comprehensible to pilots.*

As automation becomes more complex and integrated, with more potential interactions among modes, pilots must be assisted to understand the implications of those interactions, especially to interactions which can be potentially hazardous at a critical point in flight. Systems need to be as error resistant as possible in this respect, for the likelihood that pilots will remember all such potential interactions is not high if they are not encountered frequently. The memory burden imposed by complex automation is considerable; infrequently-used knowledge may not be immediately available when it is needed. (See pp. 21, 23, 24, 53, 55, 74-75, WC 1, 12, 14, 15.)

- *Alerting and warning systems should be as simple as 'foolproof' as possible.*

Warning systems for discrete failures do not present a particular problem; whether reconfiguration should be autonomous remains an open question awaiting experience with the MD-11 systems. The problem of quantitative warning system sensitivity and specificity has been discussed. False or nuisance warnings must be kept to reasonable levels to avoid the unwanted behavioral effects of excessive alarms.

At the risk of providing pilots with more information than they need to know, we believe (as did Wiener and Curry) that it may be appropriate to provide pilots with trend information before a parameter reaches a level requiring action, to improve their awareness of a potentially serious situation. This serves the added purpose of increasing their trust of the automated monitoring systems. We have suggested some ways in which trend information might be provided on simplified system displays.

TCAS provides traffic alerts with respect to traffic that may in the near future pose an imminent hazard, which gives pilots time to attempt visual acquisition of the traffic. An avoidance maneuver is advised if the traffic thereafter is assessed as a serious threat. Such systems increase pilot involvement, but this can pose a problem under conditions of high workload. It is possible that "low" and "high" sensitivities could be used during short and longer flights, or that non-critical alerts could be inhibited during flight at low altitudes, as is already done in newer aircraft.

When warnings are provided and response time is not critical, many pilots will attempt to evaluate the validity of the warning. Means should be provided for them to do so quickly and accurately.

Warnings and alerts must be unambiguous. When common signals are used to denote more than one condition (as are the master caution and master warning signals), there must be a clear indication of the specific condition which is responsible for the alert. (See pp. 23, 25, 38-39, 44-45, 48, 76, WC 11, 12, 13, 14.)

- *Less information is generally better than more information, if it is the right information for a particular circumstance.*

There is no conflict between our guideline of keeping the pilot informed and the recognition that too much information may prevent the pilot from assimilating the most important information. It is a matter of understanding what the pilot needs to know at a particular time or in a particular situation. Cockpit designers have generally done a commendable job of providing the most important information; they have not always done as well in keeping that information at the forefront of the pilot's awareness or in reducing the amount of non-essential information.

Less information is generally better than more information, but only insofar as no critical element of situation awareness is neglected. Selective de-cluttering of primary flight displays, analogous to what has been done with navigation displays, should be considered; as indicated in the text, more integrated PFDs are under study. See also the description of the "dark cockpit" concept on page 25. (See pp. 10, 17, 26, 33, 36-37, 39, 41, 43-44, 46, 48, 49, 77, 80, 82.)

- *Integration of information does not mean simply adding more elements to a single display.*

Integration in psychology means "the organization of various traits into one harmonious personality." An integrated display combines disparate information elements into a single picture that renders unnecessary many cognitive steps the pilot would otherwise have to perform to obtain a concept. It thus relieves the pilot of mental workload. Primary flight displays are not integrated; rather, they combine information previously shown on many instruments on a single screen. The elements, however, are still discrete and the mental workload of adding aircraft state is still required.

Clutter in displays is undesirable for the pilot may fail to notice the most important information or may focus on less important data. It is for this reason that we have suggested

that fairly radical de-cluttering of the PFD would still provide the pilot flying at cruise on autopilot with the information required to monitor the autopilot and return to the control loop rapidly if required.

Subsystem displays can also be made more simple and intuitive. Again, the controlling variable should be what the pilot needs to know under particular circumstances. As long as all information necessary to take over manual control of these systems is available when required, it is not necessary that other data be visible in circumstances where they are not central to the pilot's tasks, though we believe that power information, perhaps in simplified form, is needed at all times because it is an element of flight path control. (See pp. 34-35, 37-38, 39, 42, 44, 47, 54-55, 77, WC 12.)

- *Automation poses additional monitoring requirements; insure that pilots are able to monitor both the status of the automation and the status of the functions controlled by that automation.*

On page 46, it was asked whether displays should show the position of a switch, or the position of the device controlled by that switch. Should automation status be announced, as well as the status of the function being controlled? One can argue that it should be, by some means. While the "dark cockpit" concept (no annunciations as long as everything is normal) has distinct advantages in preventing information overload, no information can mean either that everything is normal or that the annunciator has failed. No information is quite different from negative information. In the case of subsystems, where nothing happens for long periods of time, pilots need some type of reassurance that the automation is still monitoring the systems.

Automation can fail covertly as well as overtly, and in either case, the pilot must become, or be ready to become, a controller rather than a manager. To do so, he or she must know by some means that the automation has failed, and the condition of the controlled elements or functions. (See pp. 33-34, 40, 48, 82, WC 5, 9, 10.)

- *Emphasize information in accordance with its importance.*

The most important information should be most obvious and most centrally-located. Information relevant to aircraft control deviations, power loss or impending collisions with obstacles is always more important than information concerning other facets of the operation. Symbolic information should be redundantly coded (shape, size, color, use of two or more sensory modalities) to insure that it is detected. Auditory (sounds) or tactile information displays can be used to reinforce, or in some cases to substitute for, visual information; this can be particularly useful during periods of high visual workload (p. 38).

It should be noted that a strenuous and largely successful attempt has been made to decrease the large number of discrete auditory warnings that were present in older cockpits. The use of discrete voice warnings is increasing, however: GPWS, TCAS and windshear alerts all incorporate voice signals, and an increasing number of aircraft also incorporate synthetic voice altitude callouts on final approach. This may be less of a potential problem as digital data link replaces some of the voice communications now required, but there remains the potential for interference among voice messages, as well as the potential for overuse of voice signals leading to diminished attentiveness to voice emergency messages.

The question of tactile information transfer has been brought to the fore by the A320 control systems (p. 23,24). The two pilot sidestick controllers are not interconnected, and therefore do not provide information concerning control inputs from the other side of the cockpit. Because the airplane utilizes a load factor demand control law, pilots cannot detect changes in trim from control column pressures. Also, the thrust levers do not move when the

- autothrust system changes engine power. The discussion points out that this may be appropriate automation and that companies flying this airplane do not manifest concern regarding these features, but it is also necessary to recognize that certain elements of the feedback previously provided to pilots are not present in this airplane. Continued scrutiny of A320 operations is needed to determine whether the absence of this feedback mode has any undesirable consequences, or whether the redundancy of the information it provides in other aircraft is not truly necessary. (See pp. 26, 35, 45, 77, WC 12.)
- *Design automation to insure that critical functions are monitored as well as executed.*

The safety benefits of independent monitoring are indisputable. ATC radar permits controllers to monitor flight path control; TCAS permits pilots to monitor controller actions. There are functions that are not independently monitored at this time; airplane acceleration with respect to runway remaining during takeoff is one, ILS guidance during instrument approaches is another. A third is aircraft position on the airport surface, at most facilities. Monitoring of input to aircraft systems, especially the FMS, remains a problem despite the monitoring capability provided by map displays. In the first two cases mentioned, new technology will be required. In the latter case, FMS software could be provided to monitor, as well as assist in, pilot interactions with the system. Where critical errors could compromise safety, independent monitoring of inputs (perhaps by downlinking of FMS data for comparison with ATC clearance data) should be enabled.

It is not clear at this point in time that airplane-to-ATC digital data link will be used to confirm that clearance data has been received and entered into the FMC correctly. Such a link could also be used to confirm that manually-entered flight plan data conforms to ATC intentions. If such a monitoring link is not provided for, an important element of redundancy will have been lost. (See pp. 48, 56, 78, 79, WC 9.)

- *Consider the use of electronic checklists to improve error resistance and tolerance.*

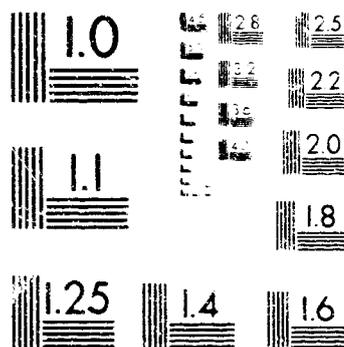
Depending on how they are implemented, electronic checklists have the potential to improve error resistance, by performing checklists on command, and error tolerance, by reminding pilots of checklists that need to be performed and by providing reminders of items not completed. Checklist usage is known to be somewhat variable (ref. 74) and failures to perform checklists have been associated with serious mishaps (refs. 10,11). "Sensed" checklists (those that verify that most or all items have been completed) will be more error tolerant than those that rely entirely on pilot confirmation of actions taken, and this may suggest a desirable minimum architecture for such modules. On the other hand, data from recent checklist studies suggests that automated checklists may reduce pilot vigilance for aircraft system faults (ref. 71). (See pp. 48-49, WC 9.)

Guidelines for Human-Centered Management Automation

Management automation has been a remarkably successful tool in the cockpit; the development of air traffic automation will further improve its utility and effectiveness. It has made the aviation system much more error resistant, though it has also enabled new errors in the cockpit, as does any new equipment that must be operated by humans. We offer the following guidelines for future flight management systems.

2 OF 2

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
ANSI and ISO TEST CHART No. 2

- ***Management automation should make airplanes as easy to manage as they are to fly.***

The major problem with flight management systems is that they are often cumbersome to operate. Under some circumstances, it is easier to operate without them than to use them, with the predictable result that they are apt to be bypassed under these circumstances. This is a pity, for the error resistance that they bring to flight path management is also bypassed. One partial solution to this problem is to improve the interfaces between system and pilot so that they can be manipulated more easily.

This will not be a trivial task, for it may require establishing a different level of interface between the pilot and the system, one which involves a high-level interaction rather than the present point-by-point description of desired ends. On the other hand, data link may enable a higher-level interaction and may even require it for effective interaction with ATC, most of which may be through the FMS.

Within the constraints of present-generation systems, efforts to improve system operability in high workload segments of flight would be most helpful to pilots, and would improve system safety. The problem of manually tuning navigation radio aids rapidly has been mentioned; providing alternate interfaces through which such tasks could be accomplished more readily is worthy of consideration. (See pp. 27-28, 29, 54, 55.)

- ***Flight management system interfaces must be as error tolerant as possible.***

In view of the known problems in data entry, FMS software should accomplish as much error trapping as is possible. Some ways of doing this have been suggested above. When data link is available, the data entry process may be simplified, but that does not necessarily imply that data entry errors will be eliminated. (See pp. 52, 53.)

As noted earlier, CDUs will refuse to accept incorrectly-formatted entries, but they do not provide feedback as to why an entry was rejected. If the computer knows, why doesn't it tell the pilot? Some data entry errors are obvious, but others may be less obvious and pilots may be tired or distracted by other problems.

- ***Future flight management system and aviation system automation must insure that the pilot cannot be removed from the command role.***

We have indicated our concern that increasing automation of the ATC system and increasing integration of the ground and airborne elements of that system have the potential to bypass the humans who operate and manage the system. One way to guard against this is to design future flight management systems so that the pilot is shown the consequences of any clearance before accepting it; another is to insure that the pilot must actively consent to any requested modification of flight plan before it is executed. A third, more difficult way is to make it possible for pilots to negotiate easily with ATC on specific elements of a clearance, such as altitude changes, rather than having to accept or reject an entire clearance or modification. All three, and possibly other ways as well, may be required to keep pilots firmly in command of their operations. (See pp. 53, 54.)

These steps will require more than simply software changes. They will require careful negotiations between the operating community and air traffic management system designers. In view of the rapidity with which the enabling technology is being pursued, the long-term goals and objectives of system designers and planners need to be known with precision. We do not believe that they have been set forth with sufficient clarity thus far, and we believe also that the consequences of fundamental changes in the locus of command of the system are so major as to require consensus before proceeding farther with system design.

- *Insure that flight operations remain within the capacities of the human operator.*

There are a very few flight maneuvers that require such precision that they have been entrusted only to automation. Category II and III ILS approaches (approaches when ceilings are less than 200 feet and visibilities are less than 1/2 mile) are an example. It has been generally accepted that pilot perceptual capabilities may not be sufficient to permit a safe landing from approaches under these very bad weather conditions. With these exceptions, however, pilots have not been asked to engage in operations that they cannot complete unaided.

The limited capacity of the airspace system has motivated intensive efforts to increase system throughput by making better use of presently-available runways and terminal airspace. As noted earlier, this includes studies of closely-spaced parallel approaches, the use of more complex approach paths, closer spacing in the terminal area, and other stratagems. At least some of these maneuvers will require extreme precision in flight path control; it is likely that automation will be called upon to perform them, and possible that it will be required.

This will be a safe stratagem if and only if pilots are provided with monitoring capability sufficient to maintain full situation awareness throughout the performance of the maneuvers, and with ways of escaping from the maneuvers safely and expeditiously in the event of a contingency either within the airplane or the system. New monitoring automation and displays may well be necessary if pilots are to remain in command during such maneuvers. We must confess our concern about an automated ATC system which requires that controllers *assume* that the automation has provided a conflict-free flight path for controlled traffic. (See pp. 56-57, 63, 95.)

Some Thoughts on Aircraft Automation

What follows is some comments that need to be made but that do not seem to fit elsewhere in this document. They are not conclusions; rather, they are issues that need to be considered by designers and operators, and perhaps by the human factors research community as well.

The use of artificial intelligence in future automation: We have made reference in several places in this document to the development of decision support or decision making systems as a future thrust in aircraft automation. Despite the promise of artificial intelligence (AI) technology in limited applications to date, AI remains a promise—an exciting one, but one whose bounds we do not yet understand. It is our belief that truly “smart” systems will find their way into the cockpit only slowly, and that those applications will be accepted by aircraft manufacturers only after protracted evaluation in less safety-critical environments. This is as it should be; the paramount interest in safety of all members of the aviation community requires a considerable degree of conservatism with respect to new and largely untested technologies.

This, of course, suggests that cognitive systems may be a long time coming, and that the introduction of smart systems should initially be for the control or management of non-critical functions. AI systems for the management of information in electronic libraries have been suggested; this might be such an application. It has been implied here that decision making systems should probably not be adaptable, because that would decrease their predictability and the human operator needs automated systems that are predictable. Pilots admittedly adapt to inexperienced copilots who learn as they accumulate operating experience, but the pilot in command is likely to be less confident of an inanimate system whose inner workings are less clear.

In an effort to take advantage of decision support technology without foreclosing the decision authority of the human operators, researchers have turned to decision-aiding systems that assist both pilots and air traffic controllers in decision-making (refs. 64, 86, 105). These systems provide options to the human operator, based on understood rules, but they leave decisions about the use of those options in the hands of the operator. (See also p. 88.)

The effects of automation on human operators: We have referred to the considerable and growing literature on human-centered workplaces. Cooley, among others, has discussed the problem of “deskilling” in highly automated environments. Aviation is certainly such an environment, though it differs in appreciable respects from the usual production environment. Nonetheless, automation does cause behavioral and attitudinal effects over time in those who work with it. Depending on how it is built and operated, these effects can range from a sense of growing mastery over another complex machine system across the spectrum to complacency and boredom in the face of tasks made routine and mechanical.

Scientists and physicians in the Soviet Union who have worked extensively with cosmonauts during long missions report that under the severe confinement and other stresses inherent in such missions, their charges become increasingly intolerant of boring, repetitive, routine tasks, to the extent of severely diminished performance (ref. 106). On the other hand, they remain capable of being stimulated and challenged by novel, intellectually demanding tasks even after many months of exposure in this most difficult and constrained environment. It is their belief that great care must be taken to insure that tasks remain challenging and stimulating.

There is much that is boring and repetitive in the cockpit environment as well, especially in long haul overwater flying. Few tasks are more soporific than watching a highly automated vehicle drone on for many hours, directed by three inertial navigation systems all of which agree within a fraction of a mile. This boredom can be compounded by fatigue during operations that often traverse the hours of darkness and normal sleep. Maintaining involvement in such a task, let alone a sense of challenge and intellectual demand, will be a real challenge to cockpit designers, but it must be met. Pilots are people who like challenges and have chosen aviation because it is a

challenging occupation. If we are to keep them from becoming ineffective, we must design their tasks in such a way that they can maintain their interest in them, and thus their performance of them. This, we believe, is the foremost challenge facing those who design and shape the aircraft automation of the future.

The flight-criticality of aircraft automation: We have suggested in this document that pilots will come to rely on reliable automation. There is much evidence that they do so, though there have not been, to date, indications that the potentially deskilling effects of control automation cannot be countered by increased emphasis on manual flying for a short time before reverting to a less automated aircraft type. Will this continue to be the case in the future, as more pilots receive their initial airline exposure in highly automated aircraft? As automation becomes increasingly reliable, will pilots with considerable experience in fully functional automated aircraft remain as able to manage those aircraft when the automation is degraded? Finally, will pilots most or all of whose experience is in aircraft with highly tailored flight control systems be able to convert to other aircraft which do not provide them with the protection such systems afford?

All of these questions, like the previous section, relate to the effects of automation on human operators. They give rise to another question, perhaps more difficult to answer. In highly automated aircraft, how much automation should be considered essential for safe operation under the wide variety of circumstances that may be encountered in line operations? At present, certification requirements permit dispatch of such aircraft without substantial elements of the automation normally provided. We have indicated the reasons for this in several places. We wonder, however, whether future pilots, brought up with highly automated aircraft, will adapt as readily and effectively to the demands of a more manual style of operation as have their predecessors who graduated to automation after considerable operating experience in largely manual aircraft.

The demands of the aviation system have motivated much of the automation we now take for granted, and those demands will increase, not abate, in the future. Is it prudent, therefore, to continue to ask pilots to be prepared to operate as effectively without important tools on which they are normally expected to depend?

During certification flights, many features of automation are disabled, along with many other subsystem failures; the flights must demonstrate that the airplanes can be operated to a safe landing under circumstances unlikely to be encountered in line flying. Despite the great care with which regulatory authorities and manufacturers have approached the certification process, however, only a subset of conditions, failures, and pilots can be evaluated. Is this sample adequately representative of the population of pilots and conditions that may be encountered on the line? Does it adequately test the worst-case circumstances to which the airplane may be exposed during its long service?

The answers to these questions are not known and may never be known conclusively, given the redundancy in the system and the relative rarity of transport aircraft accidents. In this soliloquy, our concern is simply with how little automation is enough for pilots accustomed to (and in the future, perhaps accustomed only to) a great deal more. We do believe the question needs to be considered as we approach the time when highly automated aircraft supplant earlier models in the airline fleet. We have asked repeatedly in this document how *much* automation is enough, and how much may be too much. We will close by asking how *little* automation is enough? Is there an amount that is too little, given the changing demography and experience of the pilot population and the increasing demands of the aviation system?

VI: CONCLUSION

Humans must remain in command of flight and air traffic operations.

Automation can assist by providing a range of management options.

Human operators must remain involved.

Automation can assist by providing better and more timely information.

Human operators must be better informed.

Automation can assist by providing explanations of its actions and intentions.

Human operators must do a better job of anticipating problems.

Automation can assist by monitoring trends and providing decision support.

Human operators must understand the automation provided to them.

Designers can assist by providing simpler, more intuitive automation.

Human operators must manage all of their resources effectively.

Properly designed and used, automation can be their most useful resource.

This is human-centered automation.

It has been suggested in this document that automation evolution to date has been largely technology-driven. This is clearly true, but it is also unfair in one sense; designers of new aircraft in recent years have made a determined attempt to help humans do what they may not do well in the press of day-to-day operations. In doing so, they have eliminated some causes of human error, while enabling others directly associated with the new technology.

If there has been a shortcoming of automation as implemented to this time, it is perhaps that it has not been sufficiently thought out in terms of the average pilot's needs during worse-than-average conditions on the line in an air traffic system that is not yet able to take advantage of what airplanes are now able to do. That is not a criticism of the designers of the automation; rather, it implies that a more holistic view of the aviation system is necessary. Pilots fly airplanes in a complex and increasingly crowded airspace environment, working with controllers who must deal with whatever comes their way. We have automated the simple functions; it is now up to us to learn to assist the humans who manage and control the aviation system, with the intent of further enhancing their performance under the most difficult circumstances we can envision. This will be as great a challenge as any that has confronted us.

APPENDIX: AIRCRAFT MISHAPS CITED IN THE REPORT

This appendix contains a brief description of salient aspects of aircraft mishaps and incidents cited in the body of the paper. Each occurrence described here is listed in the references section.

Northwest Airlines DC9-82, Detroit Metro Airport, Romulus, MI, 8/16/87 (ref. 10)

The airplane, flight 255, crashed almost immediately after takeoff from runway 3C¹ enroute to Phoenix. The airplane began its rotation about 1200-1500 feet from the end of the 8500 ft runway and lifted off near the end. After liftoff, the wings rolled to the left and right; it then collided with a light pole located 1/2 mile beyond the end of the runway. 154 persons were killed; one survived.

During the investigation, it was found that the trailing edge flaps and leading edge slats were fully retracted. Cockpit voice recorder (CVR) readout indicated that the takeoff warning system did not function and thus did not warn the flight crew that the airplane was improperly configured for takeoff.

The NTSB attributed the accident to the flight crew's failure to use the taxi checklist to ensure that the flaps and slats were extended. The failure of the takeoff warning system was contributory. This airplane has a stall protection system which announces a stall and incorporates a stick pusher, but auto-lat extension and post-stall recovery is disabled if the slats are retracted. Its caution and warning system also provides tone and voice warning of a stall, but this is disabled in flight by nose gear extension.

Delta Airlines B727-232, Dallas-Fort Worth Airport, TX, 8/31/88 (ref. 11)

The airplane, flight 1141, crashed shortly after takeoff from runway 18L enroute to Salt Lake City. The takeoff roll was normal but as the main gear left the ground the crew heard two explosions and the airplane began to roll violently; it struck an ILS antenna 1000 ft past the runway end after being airborne for about 22 sec. 14 persons were killed, 26 injured, 68 uninjured.

The investigation showed that the flaps and slats were fully retracted. Evidence suggested that there was an intermittent fault in the takeoff warning system that was not detected and corrected during the last maintenance action. This problem could have manifested itself during the takeoff.

The NTSB found the probable cause to be the Captain's and first officer's inadequate cockpit discipline and failure of the takeoff configuration warning system to alert the crew that the airplane was not properly configured for takeoff. It found as contributing factors certain management and procedural deficiencies and lack of sufficiently aggressive action by FAA to correct known deficiencies in the air carrier's flight operations. The Board took note of extensive non-duty related conversations and the lengthy presence in the cockpit of a flight attendant which reduced the flight crew's vigilance in ensuring that the airplane was properly prepared for flight.

Aeromexico DC-10-30 over Luxembourg, 11/11/79 (ref. 12)

During an evening climb in good weather to 31,000 ft enroute to Miami from Frankfurt, flight 945 entered pre-stall buffet and a sustained stall at 29,800 ft. Stall recovery was affected at 18,900 ft. The crew performed a functional check of the airplane and after finding that it operated properly continued to its intended destination. After arrival, it was discovered that parts of both outboard elevators and the lower fuselage tail maintenance access door were missing.

¹ Runways are numbered to indicate their magnetic heading to the nearest 10°; 3=30° (actually from 26-35°). Parallel runways also have letter designators: L=left, C=center, R=right.

The flight data recorder showed that the airplane slowed to 226 kt during an autopilot climb, quite possibly in vertical speed mode rather than indicated airspeed mode. Buffet speed was calculated to be 241 kt. After initial buffet, the #3 engine was shut down and the airplane slowed to below stall speed.

The NTSB found the probable cause to be failure of the flight crew to follow standard climb procedures and to adequately monitor the airplane's flight instruments. This resulted in the aircraft entering into prolonged stall buffet which placed it outside the design envelope.

Indian Airlines Airbus A320, Bangalore, India, 2/14/90 (ref. 13)

(Official report not available) This airplane crashed short of the runway during an approach to land in good weather, killing 94 of 146 persons aboard including the pilots. The best available data indicate that the airplane had descended at idle power in the "idle open descent" mode until shortly before the accident, when an attempt was made to recover by adding power but too late to permit engine spool-up prior to impact. The airplane was being flown by a Captain undergoing a route check by a check airman.

The crew allowed the speed to decrease to 25 kt below the nominal approach speed late in the descent. The recovery from this condition was started at an altitude of only 140 ft, while flying at minimum speed and maximum angle of attack. The check captain noted that the flight director should be off, and the trainee responded that it was off. The check captain corrected him by stating, "But you did not put off mine." If either flight director is engaged, the selected autothrust mode will remain operative, in this case, the idle open descent mode. The alpha floor mode was automatically activated by the declining speed and increasing angle of attack; it caused the autothrust system to advance the power, but this occurred too late for recovery to be affected before the airplane impacted the ground.

China Airlines B747-SP, 300 miles northwest of San Francisco, 2/19/85 (ref. 14)

The airplane, flying at 41,000 ft enroute to Los Angeles from Taipei, suffered an inflight upset after an uneventful flight. The airplane was on autopilot when the #4 engine lost power. During attempts to relight the engine, the airplane rolled to the right, nosed over and began an uncontrollable descent. The Captain was unable to restore the airplane to stable flight until it had descended to 9500 ft.

The autopilot was operating in the performance management system (PMS) mode for pitch guidance and altitude hold. Roll commands were provided by the INS, which uses only the ailerons and spoilers for lateral control; rudder and rudder trim are not used. In light turbulence, that airspeed began to fluctuate; the PMS followed the fluctuations and retarded the throttles when airspeed increased. As the airplane slowed, the PMS moved the throttles forward; engines 1, 2 and 3 accelerated but #4 did not. The flight engineer moved the #4 throttle forward but without effect. The INS caused the autopilot to hold the left wing down since it could not correct with rudder. The airplane decelerated due to the lack of power. After attempting to correct the situation with autopilot, the Captain disengaged the autopilot at which time the airplane rolled to the right, yawed, then entered a steep descent in cloud, during which it exceeded maximum operating speed. It was extensively damaged during the descent and recovery; the landing gear deployed, 10-11 ft of the left horizontal stabilizer was torn off and the no. 1 hydraulic system lines were severed. The right stabilizer and 3/4 of the right outboard elevator were missing when the airplane landed; the wings were also bent upward.

The NTSB determined that the probable cause was the Captain's preoccupation with an inflight malfunction and his failure to monitor properly the airplane's flight instruments which resulted in his losing control of the airplane. Contributing to the accident was the Captain's

overreliance on the autopilot after a loss of thrust on #4 engine. The Board noted that the autopilot effectively masked the approaching onset of loss of control of the airplane.

Scandinavian Airlines DC-10-30, J. F. Kennedy Airport, NY, 2/28/84 (ref. 15)

After crossing the threshold at proper height but 50 kt above reference speed, the airplane, flight 901, touched down 4700 ft beyond the threshold of an 8400 ft runway and could not be stopped on the runway. It was steered to the right and came to rest in water 600 ft from the runway end. A few passengers sustained minor injuries during evacuation. The weather was very poor and the runway was wet.

The airplane's autothrottle system had been unreliable for approximately one month and had not reduced speed when commanded during the first (Stockholm-Oslo) leg of this flight. The Captain had deliberately selected 168 kt to compensate for a threatened wind shear. The throttles did not retard passing 50 ft and did not respond to the autothrottle speed control system commands (the flight crew was not required to use the autothrottle speed control system for this approach).

The NTSB cited as the probable cause the flight crew's disregard for prescribed procedures for monitoring and controlling airspeed during the final stages of the approach, its decision to continue the landing rather than to execute a missed approach, and overreliance on the autothrottle speed control system which had a history of recent malfunctions. It noted that "performance was either aberrant or represents a tendency for the crew to be complacent and over-rely on automated systems." It also noted that there were three speed indications available to the crew: its airspeed indications, the fast-slow indicators on the attitude director, and an indicated vertical speed of 1840 ft per minute on glide slope. In its report, the Board discussed the issue of overreliance on automated systems at length (ref. 15, pp. 37-39) and cited several other examples of the phenomenon.

United Airlines DC-10-10, Sioux City, IA, 7/19/89 (ref. 25)

Enroute from Denver to Philadelphia in cruise flight at altitude, flight 232 experienced a catastrophic failure of the #2 tail-mounted engine. This led to loss of the three hydraulic systems that powered the airplane's flight controls. The flight crew experienced severe difficulty controlling the airplane, which subsequently crashed during an attempted landing at Sioux City. There were 111 fatalities out of the 296 persons on board.

The NTSB found that the probable cause was inadequate consideration given to human factors limitations in engine inspection and quality control procedures, which resulted in failure to detect a fatigue crack in a critical area of the stage 1 fan disk in the #2 engine. In subsequent simulation studies, the Board found that the damaged airplane, though flyable, could not have been successfully landed. It stated that flight crew performance was highly commendable and exceeded reasonable expectations.

United Airlines B-747-122, Honolulu, HI, 2/24/89 (ref. 26)

The airplane returned to Honolulu and landed safely after a cargo door opened in flight causing major airframe damage and an explosive decompression during which nine passengers were ejected and lost at sea. The crew donned oxygen masks after the decompression but the oxygen system had been damaged and oxygen was not available. They shut down engines 3 and 4 because of foreign object damage sustained during the failure.

The NTSB found that the door opened in flight because it was improperly latched. No fault was ascribed to the flight crew, which performed effectively under very difficult circumstances.

Aloha Airlines B-737-200 near Maui, Hawaii, 4/28/88 (ref. 27)

The airplane experienced an explosive decompression due to a structural failure of the forward fuselage at 24,000 ft while enroute from Hilo to Honolulu. Approximately 18 ft of cabin skin and structure aft of the cabin entrance door and above the passenger floorline separated from the airplane during flight. One flight attendant was swept overboard; eight persons received serious injuries. The airplane landed safely.

The NTSB found the probable cause to be failure to detect the presence of significant disbonding and fatigue damage of the fuselage of an old airplane. This accident prompted a very major study of the "aging aircraft" problem by operators, aircraft manufacturers, the FAA and NASA. Major changes in inspection and maintenance procedures have resulted.

Aircraft Separation Incidents at Atlanta Hartsfield Airport, 10/7/80 (ref. 28)

This episode involved several conflicts among aircraft operating under the direction of air traffic control in the Atlanta terminal area. In at least two cases, evasive action was required to avoid collisions. The conflicts were caused by multiple failures of coordination and execution by several controllers during a very busy period.

The NTSB found that the near collisions were the result of inept traffic handling by control personnel. This ineptness was due in part to inadequacies in training, procedural deficiencies, and some difficulties imposed by the physical layout of the control room. The Board also found that the design of the low altitude/conflict alert system contributed to the controller's not recognizing the conflicts. The report stated that, "The flashing visual conflict alert is not conspicuous when the data tag is also flashing in the handoff status. The low altitude warning and conflict alerts utilize the same audio signal which is audible to all control room personnel rather than being restricted to only those immediately concerned with the aircraft. This results in a 'cry wolf' syndrome in which controllers are psychologically conditioned to disregard the alarms."

Eastern Air Lines L-1011, Miami, FL, 12/29/72 (ref. 31)

The airplane crashed in the Everglades at night after an undetected autopilot disconnect. The airplane was flying at 2000 ft after a missed approach at Miami because of a suspected landing gear malfunction. Three flight crewmembers and a jumpseat occupant became immersed in diagnosing the malfunction. The accident caused 99 fatalities among the 176 persons on board.

The NTSB believed that the airplane was being flown on manual throttle with the autopilot in control wheel steering mode, and that the altitude hold function was disengaged by light force on the wheel. The crew did not hear the altitude alert departing 2000 ft and did not monitor the flight instruments until the final seconds before impact. It found the probable cause to be the crew's failure to monitor the flight instruments for the final 4 minutes of the flight and to detect an unexpected descent soon enough to prevent impact with the ground. The Captain failed to assure that a pilot was monitoring the progress of the aircraft at all times. The Board discussed overreliance on automatic equipment in its report and pointed out the need for procedures to offset the effect of distractions such as the malfunction during this flight (ref. 31, p. 21).

United Airlines DC-8-61, Portland, OR, 12/28/78 (ref. 32)

This airplane, flight 173, crashed into a wooded area during an approach to Portland International Airport. The airplane had delayed southeast of the airport for about an hour while the flight crew coped with a landing gear malfunction and prepared its passengers for a possible emergency landing. After failure of all four engines due to fuel exhaustion, the airplane crashed about 5 miles southeast of the airport, with a loss of 10 persons and injuries to 23.

The NTSB found the probable cause to be the failure of the Captain to monitor the fuel state and to respond properly to a low fuel state and crewmember advisories regarding the fuel state. His inattention resulted from preoccupation with the landing gear malfunction and preparations for the possible emergency landing. Contributing to the accident was the failure of the other two crew members to fully comprehend the criticality of the fuel state or to successfully communicate their concern to the Captain. The Board discussed crew coordination, management and teamwork in its report.

Pan American B-747 and KLM B-747, Santa Cruz de Tenerife, 3/27/77 (ref. 33)

The two aircraft were diverted to Tenerife, along with three others, because of a bomb threat at their destination, Las Palmas. While parked, Pan Am was blocked by KLM on the parking ramp. Visibility varied between 1000 and 5000 ft in fog. KLM taxied out using the single runway and made a 180° turn at the end in preparation for takeoff on runway 30. Pan Am followed about 6 minutes later with instructions to leave the runway at a specified taxiway enroute to the departure end. A few minutes later, after communication with the tower but without specific takeoff clearance, the KLM aircraft began its takeoff run after announcing, "We are now at takeoff," as the tower was requesting Pan Am to report clear of the runway in its taxi. Pan Am responded, "OK, we'll report when we're clear," just before the KLM airplane collided with Pan Am. There were 574 fatalities among the 644 persons on board the two aircraft.

The Spanish Commission of Accident Investigation found that the KLM Captain took off without clearance, did not obey the tower's "stand by" order, did not interrupt his takeoff on learning Pan American was still on the runway, and in reply to his flight engineer's query regarding Pan Am's position, affirmed that Pan Am had left the runway. It was noted that the Captain was an extremely experienced flight instructor who had not done much route flying in some time; the first officer had limited 747 flight experience. The KLM crew was very near its duty time limits; to have delayed would have required the crew and passengers to remain in Tenerife overnight.

Delta Air Lines DC9-31, Boston, MA, 7/31/73 (ref. 36)

This airplane struck a seawall bounding Boston's Logan Airport during an approach for landing after a flight from Burlington, VT to Boston, killing all 89 persons on board. The point of impact was 165 ft right of the runway 4R centerline and 3000 ft short of the displaced runway threshold. The weather was sky obscured, 400 ft ceiling, visibility 1 1/2 miles in fog.

The CVR showed that 25 sec before impact, a crewmember had stated, "You better go to raw data; I don't trust that thing." The next airplane on the approach, 4 minutes later, made a missed approach due to visibility below minimums. The accident airplane had been converted from a Northeast Airlines to a Delta Air Lines configuration in April, 1973, at which time the Collins flight director had been replaced with a Sperry device; there had been numerous writeups for mechanical deficiencies since that time. The flight director command bars were different (see fig. 11, page 20 for the two presentations), as were the rotary switches controlling the flight director. The crew were former Northeast Airlines pilots. If the crew had been operating in the go-around mode, which required only a slight extra motion of the replacement rotary switch, the pilot flying would have received steering and wing-leveling guidance only, instead of ILS guidance. Required altitude callouts were not made during the approach.

The NTSB found the probable cause to be the failure of the crew to monitor altitude and its passage through decision height during an unstabilized approach in rapidly changing meteorological conditions. The unstabilized approach was due to passage of the outer marker above the glide slope, fast, in part due to nonstandard ATC procedures. This was compounded by the flight crew's preoccupation with questionable information presented by the flight director system.

The Board commented that, "An accumulation of discrepancies, none critical (in themselves), can rapidly deteriorate, without positive flight management, into a high-risk situation...the first officer, who was flying, was preoccupied with the information presented by his flight director system, to the detriment of his attention to altitude, heading and airspeed control..."

Swift Aire Aerospatiale Nord 262, Marina Del Rey, CA, 3/10/79 (ref. 37)

This commuter aircraft was taking off at dusk from Los Angeles enroute to Santa Maria, CA, when a crewmember transmitted "Emergency, going down" on tower frequency. Witnesses stated that the right propeller was slowing as the airplane passed the far end of the runway; popping sounds were heard as it passed the shoreline. The airplane turned north parallel to the shoreline, descended, ditched smoothly in shallow water, and sank immediately. The cockpit partially separated from the fuselage at impact. The accident was fatal to the two crewmembers and one passenger.

The flaps were set at 35°, the right propeller was fully feathered and the left propeller was in flight fine position. It was found that the right propeller pitot pressure line had failed; the line was deteriorated and would have been susceptible to spontaneous rupture or a leak. The left engine fuel valve was closed (it is throttle-actuated). Once the fuel valve has been closed, the engine's propeller must be feathered and a normal engine start initiated to reopen the valve. The aircraft operating manual did not state this and the pilots did not know it.

The NTSB found that the right engine had autofeathered when the pitot pressure line had failed; the pilots shut down the left engine shortly thereafter, probably due to improper identification of the engine that had failed. Their attempts to restart the good engine were unsuccessful because of their unawareness of the proper starting sequence after a fuel valve has been closed. Engine failure procedures were revised following this accident.

Air France Airbus A320, Mulhouse-Habsheim, France, 6/26/88 (ref. 44)

This airplane crashed into tall trees following a very slow, very low altitude flyover at a general aviation airfield during an air show. Three of 136 persons aboard the aircraft were killed; 36 were injured. The Captain, an experienced A320 check pilot, was demonstrating the slow-speed maneuverability of the then-new airplane.

The French Commission of Inquiry found that the flyover was conducted at an altitude lower than the minimum of 170 ft specified by regulations and considerably lower than the intended 100 ft altitude level pass briefed to the crew by the captain prior to flight. It stated that, "The training given to the pilots emphasized all the protections from which the A320 benefits with respect to its lift which could have given them the feeling, which indeed is justified, of increased safety...However, emphasis was perhaps not sufficiently placed on the fact that, if the (angle of attack) limit cannot be exceeded, it nevertheless exists and still affects the performance." The Commission noted that automatic go-around protection had been inhibited and that this decision was compatible with the Captain's objective of maintaining 100 ft. In effect, below 100 ft, this protection was not active.

The Commission attributed the cause of the accident to the very low flyover height, very slow and reducing speed, engine power at flight idle, and a late application of go-around power. It commented on insufficient flight preparation, inadequate task sharing in the cockpit, and possible overconfidence because of the envelope protection features of the A320.

Delta Air Lines B-767, Los Angeles, CA, 6/30/87 (ref. 52)

Over water, shortly after takeoff from Los Angeles, this twin-engine airplane suffered a double-engine flameout when the captain, attempting to deactivate an electronic engine controller in response to an EEC caution light, shut off the fuel valves instead. The crew was able to restart the engines within one minute after an altitude loss of several hundred feet. The fuel valves were located immediately above the electronic engine control switches on the airplane center console, though the switches were dissimilar in shape.

The FAA thereafter issued an emergency airworthiness directive requiring installation of a guard device between the cockpit fuel control switches.

United Airlines B-767, San Francisco, CA, 3/31/86 (ref. 52)

This airplane was passing through 3100 ft on its climb from San Francisco when both engines lost power abruptly. The engines were restarted and the airplane returned to San Francisco, where it landed without incident. The crew reported that engine power was lost when the flight crew attempted to switch from manual operation to the engine electronic control system, a procedure which prior to that time was normally carried out at 3000 ft during the climb. The EEC switches are guarded. It is believed that the crew may have inadvertently shut off fuel to the engines when they intended to engage the EEC, as in the incident cited immediately above.

Delta Air Lines L-1011, Los Angeles, CA, 4/12/77 (ref. 63)

This airplane landed safely at Los Angeles after its left elevator jammed in the full up position shortly after takeoff from San Diego. The flight crew found themselves unable to control the airplane by any normal or standard procedural means. They were able, after considerable difficulty, to restore a limited degree of pitch and roll control by using differential power on the three engines. Using center engine power to maintain pitch and wing engines differentially to maintain directional control, and verifying performance at each successive configuration change during an emergency approach to Los Angeles, the crew succeeded in landing the airplane safely and without damage to the aircraft or injury to its occupants.

Korean Air Lines B-747 over Sakhalin Island, USSR, 9/13/83 (ref. 66)

The airplane was destroyed in cruise flight by air-to-air missiles fired from a Soviet fighter after it strayed into a forbidden area enroute from Anchorage, AK to Seoul, Korea. The airplane had twice violated Soviet airspace during its flight. The flight data and cockpit voice recorders were not recovered from the sea. After extensive investigation by the International Civil Aviation Organization, it was believed that its aberrant flight path had been the result of one or more incorrect sets of waypoints loaded into the INS systems prior to departure from Anchorage.

Delta Air Lines L-1011/Continental Airlines B-747 over Atlantic Ocean, 7/8/87 (ref. 67)

These airplanes experienced a near mid-air collision over the north Atlantic ocean after the Delta airplane strayed 60 miles off its assigned oceanic route. The incident, which was observed by other aircraft but not, apparently, by the Delta crew, was believed to have been caused by an incorrectly inserted waypoint in the Delta airplane's INS prior to departure.

Air Florida B-737, Washington National Airport, DC, 1/13/82 (ref. 68)

This airplane crashed into the 14th Street bridge over the Potomac River shortly after takeoff from Washington National Airport in snow conditions, killing 74 of 79 persons on board. The airplane had been de-iced 1 hour before departure, but a substantial period of time had elapsed

since that operation before it reached takeoff position. The engines developed substantially less than takeoff power during the takeoff and thereafter due to incorrect setting of takeoff power by the pilots. It was believed that the differential pressure probes in the engine were iced over, providing an incorrect (too high) EGT indication in the cockpit. This should have been detected by examination of the other engine instruments, but was not perceived by the captain flying.

The NTSB found that the probable cause of the accident was the flight crew's failure to use engine anti-ice during ground operation and takeoff, their decision to take off with snow/ice on the airfoils, and the captain's failure to reject the takeoff at an early stage when his attention was called to anomalous engine instrument readings. Contributing factors included the prolonged ground delay after deicing, the known inherent pitching characteristics of the B-737 when the wing leading edges are contaminated, and the limited experience of the flight crew in jet transport winter operations.

Delta Air Lines L-1011-385-1, Dallas-Fort Worth Airport, TX, 8/2/85 (ref. 83)

This airplane crashed during an approach to landing on runway 17L. While passing through a rain shaft beneath a thunderstorm, the flight encountered a microburst which the pilot was unable to traverse successfully. The airplane struck the ground 6300 ft north of the runway. The accident was fatal to 134 persons; 29 survived.

The NTSB found the probable cause to be the flight crew's decision to initiate and continue the approach into a cumulo-nimbus cloud which they had observed to contain visible lightning, a lack of specific guidance, procedures and training for avoidance and escape from low-altitude wind shear, and lack of definitive, real-time wind shear hazard information.

Northwest Airlines B-727 and DC-9, Detroit Metro Airport, MI, 12/3/90 (ref. 84)

These two aircraft collided while the 727 was taking off and the DC-9 was lost on the airport in severely restricted visibility. Both aircraft were on the ground. The accident site was not visible from the tower due to fog; ASDE was not available. The investigation is not complete at this time.

US Air B-737 and Skywest Fairchild Metro, Los Angeles, CA, 2/1/91 (ref. 84)

This accident occurred after the US Air airplane was cleared to land on runway 24L at Los Angeles while the Commuter Metro was positioned on the runway at an intersection awaiting takeoff clearance. There were 34 fatalities and 67 survivors in the two aircraft. The Metro may not have been easily visible from the control tower; airport surface detection radar equipment (ASDE) was available but was being used for surveillance of the south side of the airport. The controller was very busy just prior to the time of the accident.

The NTSB investigation of this accident is underway at this time, but it is reported that the controller cleared the Metro into position at an intersection on runway 24L, 2400 ft from the threshold, two minutes before the accident. One minute later, the 737 was given a clearance to land on runway 24L. It is believed that the stroboscopic anti-collision lights on the Metro were not operating at the time of the crash, as it had not yet received its takeoff clearance.

Continental Airlines DC9-14, Denver, CO, 11/15/87 (ref. 88)

This airplane crashed immediately after takeoff on runway 35L enroute from Denver to Boise, ID. The weather was sky obscured, ceiling 300 ft, visibility 3/8 mile in moderate snow and fog, winds from 030° at 10 kt, gusting to 18 kt, runway 35L visual range 2200 ft. The airplane had been de-iced 27 min before takeoff. It rotated rapidly and crashed immediately after leaving the ground. There were 28 fatalities; 54 persons survived.

During the investigation, it was found that the flight had not requested taxi clearance and the tower was unaware of its taxi to the de-icing pad. The Captain's experience in the airplane was limited (133 hr DC9, 33 as a DC9 Captain); the first officer, who made the takeoff, had only 36 hours of jet and DC9 experience, and had been off duty for 24 days before this flight.

The NTSB found the probable cause to be the Captain's failure to have the aircraft de-iced a second time after a delay that led to upper wing surface contamination and loss of control during a rapid takeoff rotation by the first officer. Contributing causes were the absence of regulatory or management controls governing operations by newly qualified flight crewmembers. The Board questioned the Captain's decision not to have the airplane de-iced a second time and to permit the inexperienced first officer to make the takeoff under difficult weather conditions. It commented that, "Pairing of pilots with limited experience in their respective positions can, when combined with other factors, such as adverse weather, be unsafe and is not acceptable," and made recommendations to avoid such pairings.

US Air B-737-400, LaGuardia Airport, Flushing, NY, 9/20/89 (ref. 89)

This airplane crashed into a pier past the departure end of runway 31 during takeoff enroute to Charlotte, NC. Two passengers suffered fatal injuries. As the first officer began the takeoff roll, he felt the airplane drift to the left. The Captain used nosewheel steering to correct the drift. As the takeoff run progressed, the crew heard a "bang" and a continual rumbling noise. The Captain then took over control and rejected the takeoff but was unable to stop the airplane before running off the end of the runway into Bowery Bay.

The NTSB found the probable cause of the accident to be the Captain's failure to exercise command authority in a timely manner to reject the takeoff or to take sufficient control to continue the takeoff, which was initiated with a mistrimmed rudder. Also causal was the Captain's failure to detect the mistrimmed rudder before the takeoff roll was attempted.

The Board noted that the takeoff configuration warning system does not include an alarm for a mistrimmed rudder, and stated that this is proper because the aircraft is not unflyable. There were abundant chances to detect the out-of-trim condition through visual, tactile and proprioceptive means. There was also a miscommunication; the Captain said "got the steering," advising the first officer to correct the airplane's track with right rudder. The first officer heard "I got the steering," said "okay" and gradually relaxed his pressure on the right rudder pedal. It was thought that neither pilot was in full control thereafter; this problem continued after the takeoff was rejected.

The Board noted that "both pilots were inexperienced in their respective positions...the first officer was conducting his first unsupervised line takeoff in a 737 and also his first takeoff after a 39-day non-flying period. The Captain had 5525 hr total flying time, 2625 hr in the 737, but only 140 hr as a Captain in the 737-400. The first officer had 3287 hr total time, 8.2 hr in the 737-300/400. Several crew coordination problems and multiple errors by both pilots were commented upon by the Board.

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13. ABSTRACT (Maximum 200 words) This report is in large part a response to a mandate of the Air Transport Association's Human Factors Task Force, which in 1989 discussed the state of civil aircraft automation and stated, "The fundamental concern is the lack of a scientifically-based philosophy of automation which describes the circumstances under which tasks are appropriately allocated to the machine and/or the pilot." This document attempts to examine aircraft automation and its effects on flight crews. It then proposes generic guidelines for the design and use of automation in transport aircraft, in the hope of stimulating increased and more effective dialogue among designers of automated cockpits, purchasers of automated aircraft, and the pilots who must fly those aircraft in line operations. The goal is to explore the means whereby automation may be made a maximally effective tool or resource for pilots without compromising human authority and with an increase in system safety. After definition of the domain of the aircraft pilot and brief discussion of the history of aircraft automation, a concept of "human-centered automation" is presented and discussed. Automated devices are categorized as a control automation, information automation, and management automation. The elements of each are considered, followed by thoughts on the likely future of automation of that category. The environment and context of aircraft automation are then considered. The elements include the aircraft themselves, the physical and operational environment, and the human operators. System goals and guidelines for flight-deck automation set forth in a landmark paper by Wiener and Curry introduce a discussion of desirable attributes of human-centered aircraft automation, which emphasizes the bipolar nature of several pairs of desirable attributes and the tradeoffs that are inescapable in the design process. General guidelines for human-centered aircraft automation are then presented, cross-referenced to the preceding discussions. A list of references is followed by an appendix which briefly describes salient aspects of a considerable number of aircraft mishaps and incidents cited in the text of the report.				
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