AU/ACSC/138/2000-04

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

IDENTIFYING AND MITIGATING THE RISKS OF COCKPIT AUTOMATION

by

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

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Maxwell Air Force Base, Alabama

April 2000

Disclaimer

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Preface

This paper provides a brief summary of the direct costs associated with automation. It is intended to provide a framework for designers, managers, and pilots in implementing measures to mitigate these costs. Safety improvements are not the province of any one of these groups. Instead, an integrated effort between these communities is necessary to promote aviation safety. In writing this paper I have assumed that the reader has a working knowledge of glass cockpit aircraft, as well as a basic understanding of human factors issues. In order to narrow the scope of this project I have focused exclusively on automation issues arising from studies of transport aircraft. In spite of the specific focus on aviation, the issues raised here apply across a wide range of highly automated domains.

I would like to thank Lieutenant Colonel Steven A. Kimbrell for his advice and assistance on this project.

Abstract

Cockpit automation has delivered many promised benefits such as improved system safety and efficiency, however, at the same time it has imposed system costs that are often manifest in the forms of mode confusion, errors of omission, and automation surprises. An understanding of the nature of these costs as well as associated influencing factors is necessary to adequately design the future automated systems that will be required for Air Mobility Command aircraft to operate in the future air traffic environment. This paper reviews and synthesizes Human Factors research on the costs of cockpit automation. These results are interpreted by modeling the automated cockpit as a supervisory control system in which the pilot works *with*, but is not replaced by, automated systems. From this viewpoint, pilot roles in the automated cockpit provide new opportunities for error in instructing, monitoring, and intervening in automated systems behavior. These opportunities for error are exacerbated by the limited machine coordination capabilities, limits on human coordination capabilities and properties of machine systems that place new attention and knowledge demands on the human operator. In order to mitigate the risks posed by these known opportunities for error and associated influencing factors, a system of defenses in depth is required involving integrated innovations in design, procedures, and training. The issues raised in this paper are not specific to transport aircraft or the broader aviation domain, but apply to all current and future highly automated military systems.

Part 1

Background

The laws that govern the behavior of human-machine systems are, in many ways, analogous to the laws that govern our physical world. Actions that affect any one system component invariably have ripple effects and sometimes-unforeseen interactions with other system components. For example, while the evolution of powerful automated cockpit systems has allowed for the current high levels of safety and efficiency in the aviation system it has also resulted in new types of potentially serious system failures in the form of breakdowns in human-machine coordination. This paper discusses observed performance problems in the human-machine cockpit team with a goal of providing Air Mobility Command's (AMC's) designers, administrators, and operators with an understanding of the known risks associated with the automated cockpit systems that will be required to operate in the future air traffic environment. Based on this assessment of known risks, an integrated set of measures can be developed to mitigate the risks associated with the introduction of these automated systems.

The evolution of highly capable automated cockpit systems has provided substantial benefits to the aviation system. Automated cockpit systems are the driving force behind the safe, precise, and economical operations that have allowed the aviation system capacity to increase dramatically over the last 50 years while providing corresponding increases in safety and economy. Studies indicate that air travel is one of the safest transportation mediums with an accident rate of less than 2 per million departures.[1] Additionally, the introduction of automated navigation systems and the flight management computer (FMC) has provided substantial fuel savings, and in combination with automated system controllers has allowed for the elimination of the navigator and flight engineer, thus reducing training and personnel costs.

Reports estimate that over the next ten years aviation traffic growth will continue at a 5% yearly rate[2]. Since the world aviation system is already nearing capacity, significant system changes will be necessary to facilitate this anticipated growth. New and increasingly powerful automated systems will be required to implement the future air traffic environment. For example, “Free Flight” is one proposal currently under development to increase the efficiency and capacity of the aviation system by allowing pilots to fly random routes and altitudes. The implementation of such a system will require the addition of automated cockpit planning and collision avoidance aids.[3] Although many AMC aircraft are currently undergoing extensive cockpit upgrades, they will likely require further upgrades to comply with the requirements of the future air traffic environment.

In spite of these substantial observed and potential benefits, cockpit automation also imposes costs on the aviation system. These costs are frequently expressed in the form of accidents and incidents attributed to the breakdowns in coordination between the pilot and automated systems. While the overall rate of aviation accidents has declined dramatically over the last 30 years, little improvement has been seen over the last 15 years, despite the continued evolution and improvement of automated cockpit systems such as the Ground Proximity Warning System (GPWS) and Traffic Collision Avoidance System (TCAS)[4]. A closer examination of the aircraft accident data indicates that human error accounts for between 65-

85% of all accidents. In many cases, this causal human error can be attributed to inappropriate human interaction with automated systems.[5]

For example, on 24 April 1994 an Airbus 300-600 crashed while on approach to Nagoya, Japan. During the approach, the copilot inadvertently engaged the aircraft's "Go around mode" which caused the automated systems to attempt to fly away from the ground using the aircraft pitch trim system, while the pilots attempted to continue the landing approach via input to the elevator. The pilots were unable to determine that the pitch trim input of the autopilot system was causing difficulties controlling the aircraft. Additionally, the design of the A300 autopilot (at that time) did not allow the pilots to override the autopilot by use of opposing control stick pressure. Thus, the pilots and automated systems continued to struggle for control, with the aircraft eventually pitching up to near vertical, stalling and crashing on the approach end of the runway killing 264 passengers and crew.[6]

This accident illustrates a phenomena that human factors researchers term "automation surprises" - i.e. failures of the human operator to track, monitor, or anticipate the actions of automated systems leading to unintended system behavior.[7] A better understanding of the factors that contribute to these automation surprises will allow AMC to determine and counteract the risks that may arise from implementation of new automated cockpit systems. This paper will discuss the human role in automated systems and review the factors that research has shown may influence breakdowns in coordination between human and machine systems. Based on these findings, I will then discuss considerations for an integrated systems approach to counteract these risks. Since this paper focuses on automation upgrades to AMC aircraft, I will focus specifically on cockpit automation in transport aircraft. However, these findings are also applicable to the broader aviation domain, as well as other highly automated systems necessary to implement the Armed Services' Joint Vision that will be installed in a wide variety of military systems.

Notes

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Part 2

The Human Role in Automated Systems

In order to understand the risks of automation, we must first understand the relationship between humans and automated systems. While it is tempting to assume that automated systems function independently of the human operator, this is not the case. As Jordan (1963) first noted over 35 years ago, humans and machines are not independent but instead are complementary.[1] They must work together to achieve desired system performance. Even the most highly automated systems still require the presence of a human operator to monitor system performance and intervene in the case of system abnormalities and emergencies.[2] In order for humans and machines to work together to achieve system goals, they need to develop or engage in processes and activities that ensure coordination and avoid conflict. This chapter will discuss how the roles of the human operator in highly automated systems provide new opportunities for errors and undesired system performance associated with the introduction of automated systems.

Prior to the introduction of automated cockpit systems, the primary role of the pilot was to directly control aircraft performance by continuous inputs via the flight controls and throttles(s). As automated systems have become more powerful, they have gradually assumed direct control of aircraft performance, while the pilot’s role has shifted to a monitor of automated system performance. For example, other than take off and (usually) landing, most of the direct aircraft control in a modern transport aircraft is delegated to automated systems - a control scheme known as supervisory control.[3]

While this shift in roles has led to more precise and economical control of aircraft performance, it has also led in a change in the nature of observed system errors. In general, since automated systems directly control aircraft performance, errors of commission - incorrect control actions have decreased; however, errors of omission - failures of the pilot to act and intervene when required have increased.[4] In order to better understand the reasons behind this trend, and also in order to predict the errors that may be observed with the introduction of future automated systems, the following section will examine in detail the human roles in supervisory control systems and discuss the types of errors that may arise during each role.

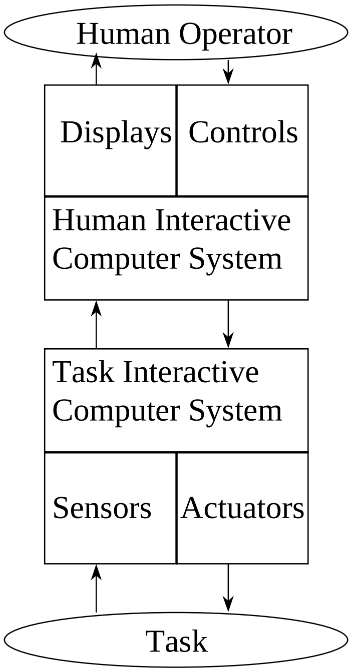

Figure 1 Human roles in supervisory control[5]

Figure 1 depicts a general supervisory control system.[6] In this type of a system, the human operator provides higher level goals to the automated system through interaction with what is known as a human interactive computer (HIC). The HIC provides the means for the operator to provide control instructions and monitor system behavior. For example, on the modern flight deck pilots provide heading, altitude, and routing targets through both the flight management computer (FMC) and the autopilot Mode Control Panel (MCP). They receive feedback on aircraft performance through the primary flight display (PFD), Navigation Display (ND) and engine indications depicted on the Engine Indication and Crew alerting System (EICAS). (For those unfamiliar with glass cockpit aircraft, see appendix A for a brief description) The HICs, in turn, interpret these pilot inputs and (based on environmental conditions/aircraft performance) provide inputs to the servos that actually control aircraft performance through what is termed task interactive computers (TICs). Since the focus of this paper is on human-machine interaction, I will focus on human interactions with the HIC.

A closer examination of human responsibilities and tasks in supervisory control systems reveals potential problems for the operator's ability to coordinate human and machine performance. Sheridan identifies five basic human roles in supervisory control: planning, teaching, monitoring, intervening, and learning.[7]

In the planning role, the operator decides which variables to manipulate, develops criteria to assess system actions, and determines constraints on activities. The planning process provides the basis for instructing automated systems and monitoring subsequent system behavior. For example, upon receipt of an Air Traffic Control (ATC) clearance, the crew plans by determining which autopilot mode and FMC or MCP input will be required to execute that clearance. Once a plan is developed, the pilot "teaches" the automated systems by providing the appropriate targets/instructions to automated systems. After providing input to the automated systems, the pilot then monitors system performance to ensure the system is performing as expected.

Monitoring refers to all activities involved in adjusting system performance in response to small deviations (trimming), as well as fault detection and diagnosis. In the current cockpit, the pilot relies primarily on information presented on the Primary Flight Display (PFD) and Navigation Display (ND) to monitor system performance. These instruments give indications of aircraft attitude, altitude, airspeed, and heading, as well as active aircraft mode(s) and command targets. The pilot determines whether/when it is necessary to intervene with machine performance (due to, for example, task completion, machine requests for assistance, or undesired system performance). Finally, based on the given plan, inputs to the system, system behavior, and interventions (if any), the pilot learns lessons that may be applied to system control in future situations.

Errors can occur at each of these five steps. During the planning stage errors occur when the pilot develops an inappropriate plan for providing data to the automated systems. These errors have two general causes. First (as is also the case in non automated systems), errors can occur when pilots fail to consider all available information (such as fuel state or existing weather) when developing the plan. Second, they may occur when pilots do not understand how the automated systems will respond to the plan. These failures may be either due to an inadequate mental model of system operation, or due to a failure to understand the current operating mode of the aircraft. Research indicates that, due to the complexity of automated systems, pilots frequently possess a faulty knowledge of automated system action, with a majority of pilots surveyed indicating that they have been surprised by automated system actions.[8] Also, pilots may possess the relevant knowledge, but may be unable to apply that knowledge in the current context - a phenomenon known as inert knowledge.[9] For example, although pilots may have been trained on programming holding patterns into the FMC database, they may be unable to retrieve and apply that information when called upon to do so during flight. Research indicates that inert knowledge is a frequent problem in automated systems, especially when the required actions are only infrequently performed.[10] Finally, pilots may develop an inappropriate plan due to a lack of knowledge regarding the operating mode of the aircraft - a phenomenon known as mode error. This problem is particularly critical since in some cases, the same operator input will result in drastically different system behavior depending on the operating mode of the aircraft. For example, an A320 crashed on approach to Strasbourg in January 1992 when the crew attempted to program the aircraft to fly a 3.0-degree glide path. However, due to the active autopilot mode, the input was interpreted as a command to fly a 3,300-foot per minute descent rate. As a result, the aircraft crashed several miles short of the runway. Mode error is a complex problem; however, it is often tied to the failure of cockpit mode indications to capture pilot attention as well as the occurrence of automatic, or uncommanded, mode transitions dictated by system software.[11]

Errors can also occur in the teaching role. These errors generally take the form of data input errors - often the incorrect entry of altitude/navigation information. This type of error is a common cause of deviations from ATC instructions. While incorrect data entry is generally considered easier to detect than the development of an incorrect plan[12], the frequent presence of a time delay between data entry and system impact can act against error detection. For example, navigation data entered prior to taxi may not affect aircraft performance until many hours into flight. The 1983 Korean AirLines shoot down over Russian air space may have been caused by such a data entry error.[13]

Errors also arise during pilot monitoring. These errors take the form of a failure to detect deviations from desired performance. These deviations from desired performance may arise from inappropriate plans, incorrect data entry, automated system malfunctions, or in response to changes in the task situation (variations in temperature/wind, system failures, etc.). Basic psychological research indicates that humans are relatively poor monitors, and often fail to detect critical events.[14] Flight simulator studies confirm that once tasks have been delegated to automated systems, human monitoring is often insufficient to detect problems.[15]

Beyond human monitoring limitations, there are two additional reasons for this relatively poor monitoring performance. First, in highly automated cockpits, research shows that pilots have gone away from a general instrument scan towards an expectations-based monitoring strategy in which they check specific cockpit indications to confirm that the system is performing as expected. As a result, pilots are less likely to detect automated system actions that go beyond pilot expectations.[16] For example, the logic in some FMC's dictates that when a change is made to the landing runway, all current vertical constraints are deleted since they may no longer be appropriate. Since this deletion is not expected, research indicates that pilots often do not check for, and thus do not detect, this situation.[17] Second, automated systems often provide feedback that is not sufficiently salient to attract pilot attention. One feature of automated systems is that they present more information than the pilot can process in the time available (information overload).[18] In the absence of salient indications (i.e. flashing lights, color changes, etc.) pilots often do not pay attention to potentially relevant information. For example, one simulator study found that nearly 25% of pilots who accessed a particular FMC page containing information required to detect an error failed to detect the error due to the poor layout of the FMC page (a cluttered display full of numbers of similar appearance).[19] In a related manner, the design of the FMC also provides barriers to detecting undesired performance. The FMC contains a wealth of performance and environmental data, but can only show a very small portion of that data at any one time. This feature is referred to as the keyhole property, and places additional demands on pilots in that they must not only realize that they need a particular piece of information, but must also remember where that piece of information is located in the FMC menu structure.[20]

Even if errors are detected, they must still be corrected to prevent undesired system performance. In order to successfully intervene in undesired system behavior, the pilot must correctly assess the nature of the problem and determine an appropriate strategy for correcting the problem. It must be realized that in many situations (for example when required performance is beyond human capabilities - e.g. a Category III ILS approach), the pilot cannot simply assume manual control, but must provide additional instructions to automated systems to correct the problem. Intervention errors occur when the pilot cannot figure out either a) why a problem has occurred, b) what to do to correct it, or c) is unable to take corrective action. For example, in the previously cited Nagoya crash, the pilots were unable to determine why the system was exhibiting the observed behavior (inadvertent selection of the go-around mode), were unable to determine the correct action (disengage the autopilot), and were prevented by system design from overriding system actions. Research indicates that pilots often fail to understand system operation and are often do not understand available methods of correcting undesired system behavior.[21] In addition to these findings, the growing inability of operators to override system action due to increased machine authority is particularly troubling. In essence, since pilots may lack the authority to override system actions they (or the designers) must be able to understand before hand the implications of selecting a given course of action - something that may be difficult or impossible, particularly if aircraft designers have failed to consider a given possibility. For example, the 1988 crash of an A-320 while on a demonstration flight in France was caused by the inability of the pilot to understand and override preprogrammed flight limits during a low altitude, low speed pass unforeseen by system designers.[22]

Finally, errors may occur in the learning process when pilots learn the wrong lessons/fail to learn from past experiences with automated systems. This will result in the formation/perpetuation of an inaccurate mental model of system activity, thus creating difficulties in future planning, monitoring, and intervening with automated systems.

Table 1 Human Roles and Opportunities for Error in Supervisory Control

Human Role	*General Difficulty*	*Caused by*	Contributing factors
Planning	Inappropriate plan developed	1. Failure to consider relevant information 2. Failure to understand automated system	a) Inadequate mental model b) Inert Knowledge c) Mode errors
Teaching	Improper data entry	Wrong data/incorrect location	a) Time delays
Monitoring	Failure to detect the need to intervene	1. Human monitoring limits 2. Expectation based monitoring 3. Inadequate feedback	a) Inadequate mental models b) Information overload c) Lack of salient indications d) Keyhole property of FMC
Intervening	Missed/incorrect intervention in undesired system behavior	1. Inability to understand: Why the problem occurred? Or what to do to correct it? 2. Unable to correct	a) Inadequate mental models b) Complex systems
Learning	Failure to learn from experiences		Inadequate mental model

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Part 3

Human-Machine Coordination

In addition to the general opportunities for error that arise from the supervisory control process, human and machine coordination abilities and requirements also create automation induced performance costs. The following section will define and describe coordination, and describe inherent human-machine coordination problems.

Coordination Theory was developed at the MIT Sloan School of Management to describe coordination and cooperation across a broad range of activities and can be used as a theoretical framework for understanding human-machine coordination. According to this theory, coordination is defined as the "management of dependencies" between the activities and goals of actors.[1] These dependencies, or potential conflicts, can take many forms including constraints on shared resources, time availability and scheduling, restrictions on simultaneous operations, as well as incompatibilities between different task and subtask elements.[2] In simpler terms, human-machine coordination entails the processes required to detect and resolve conflicts between the goals and actions of pilots and automated systems.

The variety and multiple sources of goals and actions in a typical flight complicate cockpit coordination. For example, pilot goals may include navigating from airport A to airport B, following air traffic control directives; following prescribed procedures, etc. Automated systems also hold a wide variety of goals. The pilots provide most of these goals such as heading, airspeed and altitude targets. The aircraft designers, however, provide some goals. For example, autopilots (and even aircraft control software in the most advanced aircraft) are programmed to fly above a minimum airspeed and below a maximum airspeed at all times. In addition to goals provided by the operator or designer, some machine goals may be provided by other human or machine agents. For example, data link will allow for direct communication between cockpit automation and ground-based human and machine agents.[3] Since pilots may be less aware of the goals provided by designers and outside agents, coordination of these goals and actions may be particularly difficult.

In human-human teams coordination is a cooperative endeavor in which all parties share information on ongoing tasks and goals, and actively seek to resolve misunderstandings or ambiguities. Unfortunately, automated cockpit systems possess limited communication and inferential abilities that severely constrain true cooperation among human and machine agents.[4] As a result, automated systems are unable to share the responsibility for coordinating intentions and actions due to limited machine abilities as well as the dynamic nature of the aviation domain. Therefore, pilots are primarily responsible for detecting and resolving present and future conflicts between human and machine goals and actions. This implies that pilots must understand not only machine goals and actions, but must understand how automated systems will interpret pilot actions as well. For example, in the Nagoya crash, human-machine coordination broke down when the pilots were unable to ascertain autopilot goals (to climb away from the ground) and actions (autopilot induced nose-up trim inputs). Additionally, when the pilots recognized that something was wrong, attempts to resolve the conflict were unsuccessful because they did not realize that since the autopilot was engaged in the go-around mode, it would not correctly interpret their corrective actions (in the go-around mode, the trim system locked out pilot nose down trim inputs).

Research indicates four major machine communication and design factors that contribute to breakdowns in human-machine coordination - an inability to sense operator goals, an inability to communicate machine goals, an inability to communicate a lack of clear understanding of operator inputs, and an inability to communicate proximity to the limits of automated system capabilities. First, machines generally lack an ability to sense operator goals.[5] As a result, designers are forced to make (sometimes-faulty) assumptions about pilot intentions and probable actions. This inability to sense goals has been shown to lead to a variety of potential breakdowns in coordination. For example, when a pilot changes the designated landing runway in the FMC,[6] the machine does not know, and cannot ask, whether or not this runway change will also require a change to the previously constructed vertical profile. As a result, the system design is forced to make an assumption about pilot intent. Since, in many cases, a change in runway often results in a landing in the opposite direction, the system design assumes the pilot will want to construct a new vertical profile and thus deletes the stored vertical profile. However, this design feature leads to problems when the change in runway is merely a sidestep to a parallel runway. In this case, ATC expects the pilot to retain the vertical constraints automatically deleted by the FMC. If the pilot does not realize the constraints have been deleted (as research shows is quite often the case) the result is a failure to meet an assigned altitude restriction.

Second, automatic systems do not always clearly communicate their own goals. Automated systems often provide a great deal of feedback on *what* actions they are taking, but little information on *why* they are taking those actions.[7] Feedback on machine goals is especially important because machine actions can result not only from goals provided by the pilot, but also from goals provided by system designers and other agents. As demonstrated by the Nagoya crash, pilots may be unable to resolve conflicts without knowledge of the machine goals that led to the observed discrepant behavior.

Third, unlike human crewmembers, automated systems often lack the ability to clarify ambiguous or misunderstood instructions. This is especially true when full understanding requires knowledge of other pilot goals and intentions.[8] For example, in the 1995 crash of a B757 enroute to Cali, Colombia, the crew was cleared to proceed direct to a point named ROZO. Due to crew confusion over waypoint designators, the crew entered "R" into the FMC instead of the required "ROZO". Unfortunately the point "R" corresponded to a NDB located near Bogota, nearly 100 miles in the opposite direction of intended landing. Since the FMC was unable to detect the ambiguity inherent in a command to turn in the opposite direction of the landing airport, the FMC dutifully followed this command and executed a nearly 180 degree course reversal while descending in mountainous terrain resulting in a fatal impact with terrain.[9]

Finally, automated systems do not give clear indications when they are approaching the limits of their capability.[10] While human performance often degrades gradually, thus giving other team members time to detect and compensate for impending failure, machine systems often give up suddenly without warning. As a result, pilots may have insufficient time to plan and compensate for machine failure. For example, a China Airlines B747 experienced engine failure off the coast of San Francisco engine failure above 3-engine altitude cruise altitude. While the aircraft slowly decelerated, the autopilot was forced to provide increasing control force to keep the wings level. Since the indications of autopilot effort were difficult to determine, when the crew disengaged the autopilot they were caught off guard by the control inputs required to hold level flight, resulting in a 30,000-foot altitude loss and structural damage prior to recovery.[11]

In summary, due to limited machine inferential and communication abilities, machines cannot share the responsibility for coordinating human and machine actions. As a result, the need to coordinate the actions of automated systems place additional knowledge and attentional demands on the human operator. In other words, the human operator is responsible knowing how a machine will act in a given situation, but must be able to monitor for pending conflicts with/between the large number of automated cockpit systems. Many of these conflicts arise due to inherently limited machine communication and inferential abilities that cause automated systems to misinterpret or make incorrect inferences regarding human intentions.

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[7] Norman, Donald. A. "The "problem" of automation: Inappropriate feedback and interaction, not "over-automation." *Philosophical Transactions of the Royal Society of London, B327,* 1990, 585-593.

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[9] Aeronautica Civil of the Republic of Colombia. *Aircraft accident report: Controlled flight into terrain, American Airlines Flight 965 Boeing 757-223, N651AA near Cali, Colombia December 20, 1995*. Santafe de Bogota, D.C. Colombia: Author. 1996.

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[11] Ibid., 308.

Part 4

Factors Affecting Human Coordination Activities

Effective integration of automated systems requires an understanding of the factors that may serve to limit the pilot's capacity to meet the demands of coordinating human and machine actions. In general, research indicates that most breakdowns in human-machine coordination occur in high workload, high time pressure, unfamiliar situations.[1] The following sections will discuss the role of time pressure, workload, and situation awareness in leading to breakdowns in human-machine coordination.

Workload

The amount of cognitive workload imposed by automated systems affects the pilot's ability to program, monitor, and intervene with automated systems. The relationship between human performance and workload generally follows an inverted U shaped function known as the Yerkes-Dodson law.[2] In general, human performance is poor in conditions of both low and high workload, with optimum performance occurring at moderate levels. Thus, workload can harm human performance in two ways - by either raising or lowering pilot workload away from optimum levels. When workload is too low, boredom decreases the pilot's ability to monitor automated systems. Conversely, when workload is too high, a phenomenon known as cognitive tunneling is likely to occur which serves to limit human performance.[3] Under cognitive tunneling, humans tend to focus on a relatively small number of salient cues and ignore other information sources. As a result, pilots may fail to detect the need to intervene in automated system performance, or may be unable to consider the factors required to adequately program automated systems. For example, cognitive tunneling is one explanation for the 1972 crash of an Eastern Airlines L-1011 in the Florida everglades in which preoccupation with a burned out landing gear indicator prevented the crew from detecting a gradual descent into the terrain.[4]

While automated systems are often intended to reduce pilot workload, research indicates that the introduction of glass cockpit aircraft has had little effect on overall pilot workload. The introduction of automated systems tends to redistribute, rather than reduce, pilot workload.[5] The general trend for cockpit automation is to reduce workload when it is already low - at cruise - and increase workload when it is already high - during departure and arrival, a phenomena known as “clumsy automation”.[6] This workload distribution is due, in large part, to the high cognitive demands imposed by planning and instructing automated systems, i.e., the demands of data entry associated with the frequent route and altitude changes occurring in the terminal area.

Time Pressure

The previously described crash of a B757 enroute to Cali, Colombia illustrates the effects of time pressure on the pilot’s ability to instruct and monitor automated systems. In this case, the crew was under considerable time pressure due to pilot acceptance of an unanticipated clearance to fly a straight in approach to the south (as opposed to overflying the field for an approach to the north). When the automated systems were mistakenly programmed to fly direct to the Romeo NDB (as opposed to ROZO), it took the crew almost one minute to realize that they were proceeding almost 180 degrees off of the desired course.[7]

Time pressure has several effects on the pilot’s ability to interact with automated systems. A review of judgments and decision making under time pressure found that as time pressure increases: 1) people tend to use less information, or use available information in a more shallow manner, 2) more important sources of information are given increasing weight, 3) people tend to lock in on one strategy, and, as a result, 4) performance decreases.[8] In general, these studies suggest that as time pressure increases, pilots will consider less of the available evidence when instructing, monitoring, and intervening with automated systems and may also seek less cognitively demanding methods of arriving at these decisions thus leading to breakdowns in human-machine coordination. For example, a recent simulator study found that time pressure significantly reduced pilots' ability to detect problems with the automated implementation of data link ATC clearances.[9]

Situation Awareness

In order to anticipate the actions of automated systems, the pilot must have good situation awareness - i.e., knowledge of the current and projected aircraft state and associated variables. Since automated systems, and not the pilot, actually control the aircraft the pilot may fail to develop an accurate mental picture of aircraft state and important information needed to control the aircraft. Thus, the introduction of automated systems can lead to poor situation awareness resulting in problems instructing, monitoring, and intervening in automated systems. Each of these will be discussed in turn.

First, poor situation awareness can lead to problems instructing automated systems. For example, problems of mode error (i.e., pilot actions inappropriate for the given aircraft mode such as the previously described Strasbourg accident) can attribute to poor situation awareness.[10] Second, as indicated previously, pilot monitoring in automated aircraft is based primarily on expectations of aircraft performance.[11] A lack of situation awareness regarding aircraft state or the presence of potential threats can lead to the failure to detect the need to intervene. For example, problems with situation awareness contributed to the previously described Cali crash. Due, in part, to the automated removal of certain navigation information shown on the cockpit displays following a change in waypoints, as well as a reliance on the autopilot/FMC for navigation, the crew was unsure of aircraft position, as well as the position of nearby waypoints. As a result, the crew was unaware of the close proximity of steeply rising terrain.[12]

Finally, poor situation awareness can also lead to problems with successfully intervening in automated system actions - a phenomenon known as "out of the loop syndrome."[13] For example, a recent simulator study found that the introduction of an automated system that automatically loaded data link clearances into the FMC and MCP resulted in a decreased pilot knowledge of current aircraft state, thus delaying actions to intervene in undesired performance. In this study, pilots using this automated system were less likely to detect a clearance to *descend* to an altitude *above* the current altitude. When the problem (an unexpected climb) was encountered, the lack of knowledge of current altitude resulted in delayed or misdirected intervention (e.g., attempts to trouble shoot a presumed faulty autopilot).[14]

In summary, since automated systems assume the role of directly controlling aircraft performance, pilots may encounter problems developing the situation awareness required to instruct, monitor, and intervene in system performance. However, the introduction of automated systems does not always lead to decreased situation awareness. Instead, it appears that the affects on situation awareness depend on the interaction with changes in pilot workload. Studies involving failure detection during autopilot coupled instrument approaches shows that automation may improve pilot performance to the extent that it decreases workload while not detracting from the system feedback available to the pilot.[15] Other research suggests that the introduction of automated systems may allow pilots to develop a better awareness of the strategic situation (knowledge of the general route of flight in relation to other waypoints/hazards) since the automated systems free the pilot from concentrating on the tactical details of controlling system operation.[16]

The bottom line is that the introduction of automated systems may either help or hurt pilot performance, depending on the tradeoff between reductions in pilot workload and potential decreases in pilot awareness of system operations. Additionally, the introduction of automated control systems may allow for reduced pilot awareness of the details of systems operations, but the reduction in workload associated with automated system control may free the pilot to focus attention on higher level problems. In order to assess the positive or negative effects of automation on human performance, system designers and operators must consider the effects of automation on pilot workload, as well as the consequences for, and relative importance of, tactical and strategic situation awareness.

Notes

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[13] Wickens, Christopher D. “Process control and automation.” In *Engineering Psychology and Human Performance.* New York: Harper-Collins. 1992, 504-551.

[14] Olson, Wesley A. “Supporting Coordination in Widely Distributed Cognitive Systems: The Role of Conflict Type, Time Pressure, Display Design, and Trust.” Ph.D. Dissertation, Champaign, IL: University of Illinois. 1999.

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Part 5

Machine Factors Affecting Human-Machine Coordination

In addition to the factors which have a direct effect on the pilot performance, research also indicates that many features of modern automated systems also contribute to breakdowns in human-machine coordination. Automated systems have evolved from simple systems that carried out relatively uncomplicated functions (for example early autopilot systems did little more that hold heading and altitude) into highly powerful agent-like systems that carry out multiple functions and pursue complicated goal-oriented tasks (for example the modern autopilot/ FMC can plan and execute complicated flight path trajectories). Research indicates that these highly capable modern systems possess several attributes - authority, autonomy, complexity, coupling, and low observability - that contribute to breakdowns in human machine coordination.[1] A better understanding of the impact of these factors will allow for designers and operators to make better informed design decisions regarding those factors that can be controlled, and to implement more effective measures to control the risks posed by those factors that cannot be designed out of future automated systems.

Authority

Authority describes the ability of the automated system to override/block human input.[2] Automated system authority is often intended to prevent unsafe operation (for example, systems that prevent over/underspeed conditions) or is intended to prevent human actions from interfering with automated systems operation (for example, trim systems that lock out pilot input while the autopilot is engaged). However, high levels of system authority may also prevent the pilot from intervening in the case of undesired system operation. For example, in the previously described A320 crash during a flight demonstration, the pilot could not override the preprogrammed flight limits when such a response was required to prevent impact with the ground.[3]

At a general level, high levels of machine authority may place the pilot in what is known as the responsibility-authority double bind. The responsibility-authority double bind occurs when the human operator has the responsibility for system operation, but does not have the authority to take all necessary control actions.[4] Research across a range of domains, shows that this split between authority and responsibility leads to poor system operation.[5] In the case of the modern cockpit, the pilot in command has the legal and moral responsibility for ensuring safe and effective operations, yet in some cases, may lack the ability to override the actions of automated systems. This lack of authority means that, in order to coordinate human and machine actions, the pilot must anticipate some conflicts before they occur since he or she may not be able to intervene after the fact. Given the complexity of automated systems, human cognitive limits, the dynamic nature of the environment, and the possibility of machine malfunction, it will be impossible for the pilot to anticipate machine actions in all situations. While good system design can minimize the number of situations in which pilots may have a legitimate reason to override machine actions, analysis indicates that designers cannot anticipate every possible situation.[6]

There are three general ways in which machines may limit pilot authority. First, the most obvious situation occurs when pilots are physically unable to override machine actions. For example, most fly by wire aircraft incorporate features that prevent overspeeding/overstressing the airframe. Second, pilot authority is also limited when the human effort required to override machine systems exceeds his or her capabilities.[7] For example, automated decision making aids may usurp pilot authority when the complexity of their decision processes exceeds the capacity of the human operator to accurately assess the validity of the decision. A recent study of pilot interaction with a complex cockpit flight planning aid showed that pilots often followed risky flight planning suggestions when the automated system failed to consider the projected track of hazardous weather.[8] Finally, relative difficulties reprogramming automated systems can also limit pilot authority. A recent study of glass cockpit pilots found that over 75% of reported problems overriding automated systems dealt with difficulties reprogramming automated systems rather than difficulties assuming manual control.[9]

Autonomy

Autonomy refers to the capability of automated systems to operate for long periods of time with minimal operator input.[10] For example, once programmed during pre-taxi operations, the FMC can provide navigational guidance for the duration of the flight. System autonomy creates problems by increasing the time delay between control input and associated systems response. As this time delay increases, the probability of error detection decreases.[11] In essence, since human memory decays with time, it becomes increasingly difficult for the operator to generate the expectations required to effectively monitor system performance. This problem is exacerbated in long haul flights in which relief crewmembers swap out during flight. In this case, the relief crewmembers monitor system behavior that may be the result of inputs made by a different crewmember. That input may perhaps be incorrect or may use techniques not desired by the present crew.

Complexity

As automated systems grow more powerful, they are also more complex both in terms in the number of automated components as well as the calculations required to produce system behavior.[12] This complexity makes it difficult or impossible for the pilot to understand and predict system behavior. Since an appropriate mental model of automated system operations is required for instructing, monitoring, and intervening in system behavior, system complexity can lead to problems in each of these areas. Recent surveys indicate that pilots often do not completely understand the operation of automated systems, often leading to instances of undesired system behavior.[13] The effects of complexity on the pilot's ability to control system behavior may interact with pilot experience. A recent study found that pilots with 600- 1500 hrs in the current airframe were least likely to detect the inappropriate behavior of an automated data link system. This may be due to a relative inability to generate an adequate set of expectations regarding system behavior as a result of a limited basis of personal experience which is not sufficient to compensate for lessons forgotten since going through initial training.[14]

Coupling

Closely related to complexity, coupling refers to interconnections between system components.[15] Many automated systems components receive inputs from and give commands to a number of interrelated subsystems. For example, figure 2 indicates the relation of the FMC to other cockpit systems. Coupling contributes to breakdowns in human-machine systems by limiting the pilot's ability to generate an accurate mental model of automated system actions. This interferes with instructing, monitoring, and intervening with automated systems. This is especially true since coupling often leads to automated systems doing more than expected by pilots - a situation that is particularly difficult to detect. Research shows that since pilots monitor systems primarily on the basis of their expectations of system behavior, pilots often do not monitor for and thus do not detect these situations.[16]

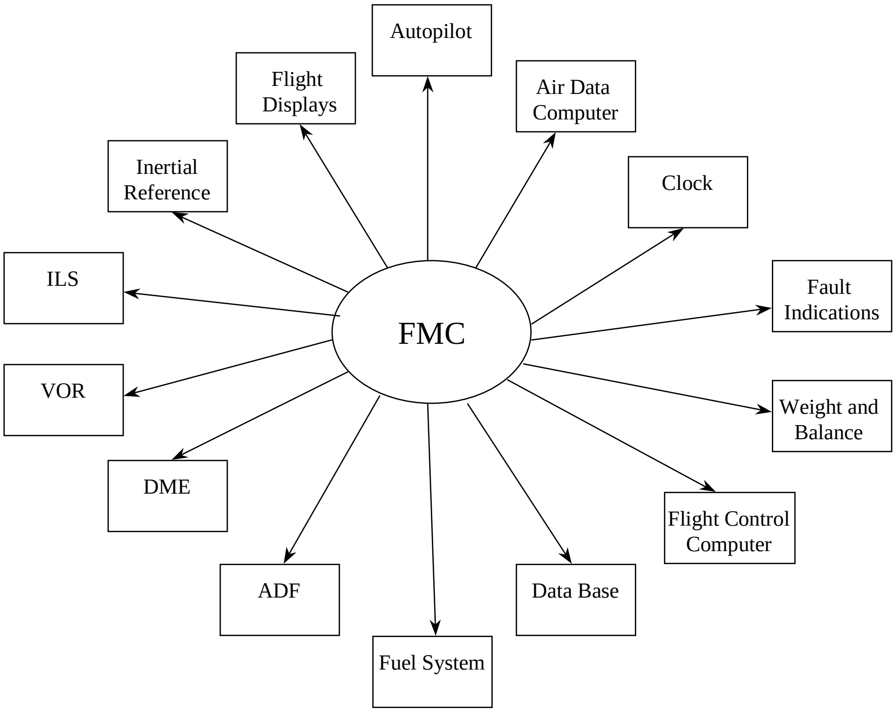

Figure 2 Systems Coupled to the FMC

Low Observability

Automated systems often provide inadequate feedback regarding their actions. The problem is not that indications do not exist, rather the problem is that the indications that do exist require an excessive amount of effort for the pilot to monitor and process - a phenomenon known as low observability.[17] It is not enough to merely present information, instead, given the large amount of information available to the operator; the system must draw operator attention to the information and present the information in a manner that requires little effort to understand. For example, in the Air China incident, the information required to allow pilots to determine that the autopilot was reaching the limits of its control authority was available to the pilots, but it was not observable. Since the cockpit displays did not draw pilot attention to the relevant information, the pilots had to not only realize the need to check the data, but also had to remember where the information was displayed. Additionally, the pilots would have had to take the additional step of comparing actual indications to their memory of the autopilot limits, since the display did not indicate the limits of autopilot authority.

In addition to monitoring difficulties, low observability can also lead to problems instructing and intervening in automated system behavior. In the instruction phase, mode errors often occur when pilots are not aware of the current aircraft mode as pointed out by the previously described Strasbourg crash.[18] Additionally, as pointed out by the Nagoya Crash, the inability to determine the current mode status can lead to an inability to successfully intervene in automated system behavior.

In summary, the attributes of many highly capable automated systems can contribute to problems instructing, monitoring and intervening in automated system action. These factors all work against the pilot's ability to develop an accurate mental model of system behavior and make it difficult to predict future behavior. While low observability can be corrected through the application of appropriate human factors principles, system design is less able to limit the effects of coupling, complexity, autonomy, and authority of automated systems. Instead, a design decision must be made whether the risks associated with a give system can be sufficiently countered by a systematic attempt to control the risks associated with implementing new automated systems.

Notes

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[3] Billings, Charles E. *Aviation automation: The search for a human centered approach*. Mahwah, NJ: Lawrence Erlbaum Associates, 1997, 310.

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Part 6

Mitigating the Risk of Automated Systems

There is no silver bullet in the effort to mitigate the risks posed by automated systems. Since accidents and incidents are not isolated actions, but instead the product of a chain of events, preventative efforts must focus on a variety of actions. James Reason's model of system failures and defenses in depth provides a useful means of visualizing this process. Figure 3 depicts accidents and incidents as the process in which managerial decisions (budgeting, priorities, hiring practices) serve as enabling conditions for unsafe acts which are expressed as accidents when they pierce weaknesses and failures in a series of system defenses (design, training, procedures, etc.) designed to guard against system failures.[1] In essence, accidents and incidents result when a chain of actions form a vector that penetrates these defenses.

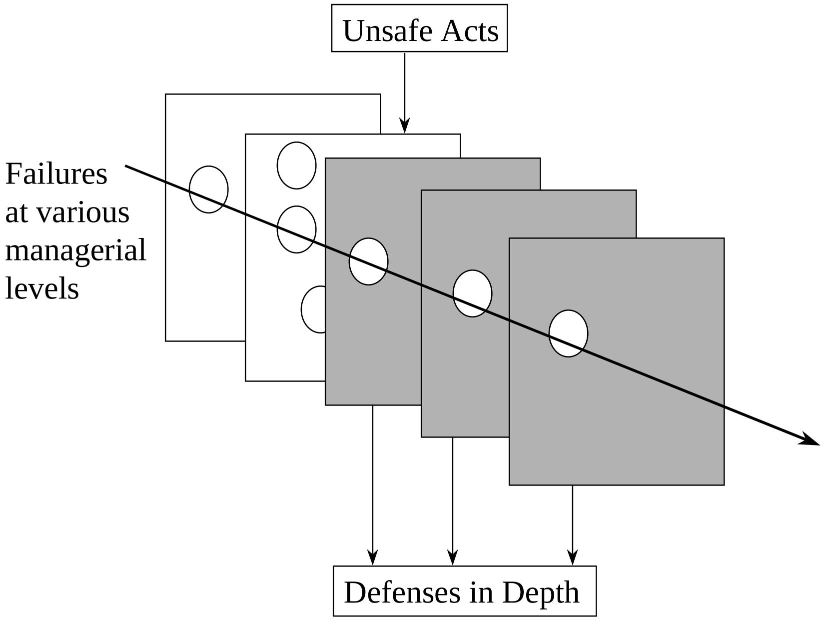

Figure 3 Defenses in depth[2]

Since a complete treatment of this model is beyond the scope of this paper, I will focus on the defenses in depth, rather than decisions made at various managerial levels. In essence, the defenses in depth can be thought of as features of design, procedures, and training, which are aimed to mitigating the risks identified in the previous chapters. The following chapter will discuss general considerations in system design, training, and procedures in order to mitigate the risks identified in human-machine coordination, limits on human performance, and factors of machine design.

Difficulties in Human-Machine Coordination

This paper identified four basic problems with human machine coordination activities, machines *cannot*: a) sense operator goals, b) communicate their own goals, c) identify/correct misunderstandings, and d) communicate when approaching the limits of their capability. A series of overlapping design, procedural and training measures must be employed to counteract these coordination problems.

Current research in cockpit automation addresses design solutions to these problems. In order for automated systems to share the responsibility for coordinating human and machine actions, they must possess a better knowledge of pilot goals and actions. The "Agenda Manager" is one effort in this direction.[3] This system uses information about pilot statements and actions to infer pilot goals. It then compares these goals to the goals and actions of automated systems to detect conflicts and identify potential misunderstandings. While this effort is only partially successful to date, it represents an important direction for future design.

Flight procedures must also compensate for the inability of machine systems to participate in the coordination process. Procedures which require the second crewmember to confirm inputs to automated systems are one step in this direction. However, research indicates that since both crewmembers share a similar awareness of the environment and the automated system, relatively few errors are caught by the second crewmember.[4] Therefore, procedures must consider the contribution made by other components of the aviation system such as Air Traffic Controllers and dispatchers.

Finally, training must emphasize and demonstrate the limits of machine coordination and communication abilities. In order to train pilots on these machine limits, they must be exposed to these situations in a realistic manner. Unfortunately, since simulator time is limited (and expensive) it is often impossible to provide this training in the simulator. Often, it is assumed that pilots will pick this knowledge up during line operations. As an alternative, the technology exists to replicate important cockpit control systems on an interactive desk-top part-task trainer. Using this technology, pilots could learn machine coordination limitations via a set of predefined illustrative scenarios flown on desk top computers in flying units or at home on personal computers.

Human limitations

This paper identified three major limitations to the human's ability to control automated systems - time pressure, workload, and situation awareness. From a design standpoint, care must be taken to look not only at the effects on overall workload, but also on workload distribution. Workload should not be allowed to concentrate in areas that are already effort intensive. Displays must also be designed to support situation awareness by indicating elements of current and future aircraft performance. Research in mode error indicates the relative importance of highlighting performance and mode changes.[5] Procedures must also be designed to compensate for known human limitations. For example, since human performance is substantially degraded under time pressure, procedures should be designed to promote adequate time available to program/monitor/intervene with automated systems. Additionally, since monitoring is often ineffective in detecting the need to intervene in automated system actions,[6] procedures should focus attention on fostering error detection during the instruction process. Finally, training must stress and demonstrate the importance of time and workload management.

Machine Factors

The autonomy, authority, complexity, coupling, and low observability of many automated systems make it difficult for the pilot to develop an accurate mental model of automated systems. From a design point of view, the problem with automation is "…inappropriate feedback and interaction, not overautomation."[7] Automated systems often do not provide adequate feedback on their actions or intentions. As a result, the pilot cannot develop an adequate mental model of system operations required to instruct, monitor, and intervene in system activities. Inappropriate interaction occurs when automated systems do not support pilot efforts to coordinate or override automated actions. Often automated systems must be complex, coupled, and autonomous in order to accomplish their intended roles. As a result, design efforts should focus on system observability (feedback) and coordinative abilities (authority).

There are three general approaches to address problems with system observability, all of which seek to minimize the effort required to interpret displayed information. First, automated systems must communicate both what they are doing and why they are doing it. For example, the development of vertical situation displays (VSD's) will allow pilots to better understand and visualize vertical path information.[8] Also, given the autonomy and authority of automated systems which may prevent or deter pilot intervention after the fact, feedback must be provided on the future intentions and actions of automated systems, especially in regards to mode changes.[9]

Second, feedback must also be designed to reduce the effort required to *detect* relevant information and ascertain its importance. Automated systems must draw pilot information to the relevant information by changes in color, intensity, auditory alerts, etc. This is especially critical when access to the relevant information is likely to require pilot-activated display changes to view the information - for example information on the EICAS or in the FMC. Additionally, information should be formatted to allow easy processing. For example, when integration of several parameters is required (such as evaluating a given vertical path) numeric information is often more difficult to process than a graphic depiction of the same data.[10]

Finally, design must also carefully consider any limitations on pilot authority. As discussed previously, these limits may be either due to the physical inability to override automated systems, or may arise when pilot override is possible, but limited by difficulties in understanding machine actions or determining the desired method of altering machine performance. When pilots cannot adequately assess the acceptability of machine actions they will likely either blindly accept machine actions, or inappropriately intervene in correct machine behavior. In order to address these problems, design (and test/evaluation) must identify and minimize limits to pilot authority. When pilot authority is limited, the benefits (i.e. stall prevention) must outweigh the potential costs. Additionally, once limitations to pilot authority have been identified, procedures and training should be developed to identify and preclude intentional operation in these regions.

Notes

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Part 7

Conclusion

While the introduction of highly capable automated cockpit has provided important contributions to system safety, precision, and efficiency, it has also imposed system costs in the forms of new opportunities for error which are expressed as breakdowns in human-machine coordination. With the introduction of automated systems, the role of the pilot has changed from system controller to system supervisor responsible for instructing, monitoring, and intervening with automated systems. An analysis of these roles as well as the capabilities, limitations, and characteristics of human and machine members of the cockpit team reveals the areas of greatest risk to system safety and performance that may be associated with the introduction of automated cockpit systems required for AMC aircraft to operate in the future air traffic environment.

In general, problems arise from the growing power, but limited coordination and communication abilities of current automated systems. As a result, the human operator is solely responsible for ensuring cooperation and resolving conflict between human and machine intentions and actions. Time pressure, workload, and problems with situation awareness can reduce the pilot's ability to execute these coordination responsibilities. Additionally, the autonomy, authority, complexity, coupling, and low observability of automated systems make it difficult for the pilot to understand and anticipate machine intentions and actions. In order to compensate for these known risks of automated systems, AMC must implement a system of defenses in depth utilizing design, training, and procedural solutions aimed at controlling the previously identified risk factors.

The issues addressed in this paper are not unique to transport aircraft or the braoder aviation domain, but instead generalize to any system that incorporates highly powerful, agent-like automated systems. One large area of future concern is the Armed Services' Joint Vision which will require the integration of information technology into a host of military systems[1]. This integration will depend heavily on automation to integrate, manage, process, and synthesize large volumes of information. The issues identified here provide an important first step for ensuring that we realize the advantages of these systems while mitigating the new opportunities for error that will be inherent in the information revolution.

Notes

[1] Joint Chiefs of Staff. *Joint Vision 2010*. Washington DC: Author. 1996, 13-15.

Appendix A

A Brief Description of the FMC and MCP

The Flight Management Computer (FMC)

The FMC Control Display Unit (FMC CDU) is the pilot’s interface with a multifunction computer system (the FMC) that allows the pilot to plan, navigate, and control the aircraft. Through interconnections with a number of onboard systems and sensors, FMC planning features provide the pilot with weather (winds/temperature), fuel, timing, and performance data (optimal altitudes, takeoff and landing speeds, etc.). The FMC also contains a worldwide data base of navigational and instrument approach data that, when combined with satellite or inertial position information, allows the pilot to determine aircraft position as well as the relative position of other navigational waypoints. Finally, interfaces with the autopilot and automatic throttle systems allow the FMC (depending on mode) to provide steering, altitude and speed commands to these systems.

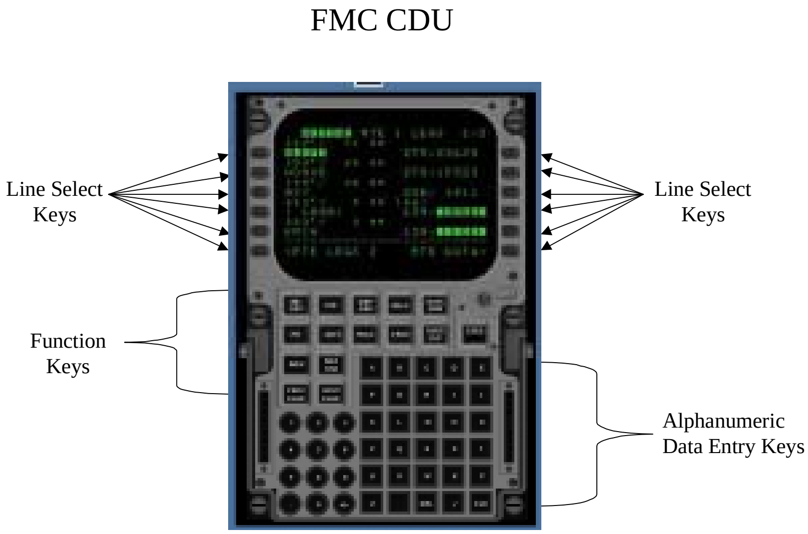


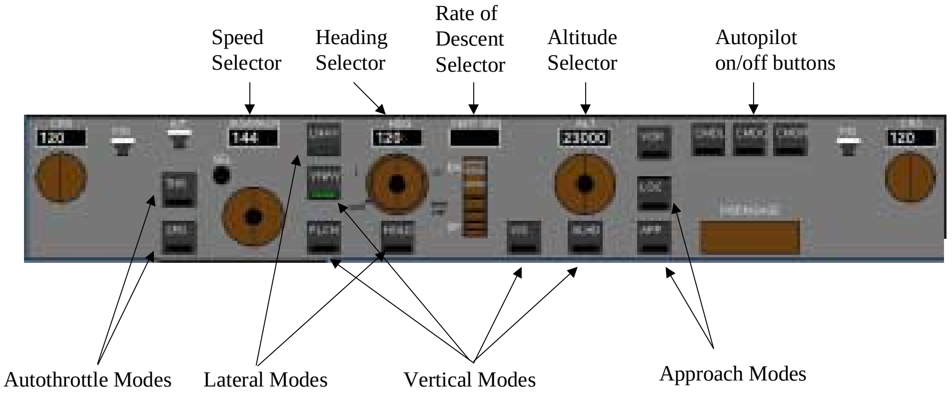
Figure 4 A typical FMC CDU

The FMC CDU allows the pilot to input or review data via a menu driven architecture. Figure 4 represents the FMC CDU similar to the one the Boeing B757 aircraft. Data presentation is limited to approximately 12 lines of data arranged on either side of the display unit. In order to support the wide range of functions available, the FMC employs a branching menu structure in which pilots can access by selecting the appropriate function key (Legs, Route, Cruise, etc.) on the associated data entry panel. Once a given function is selected, the pilot can navigate through the associated menu pages by using the “prev page” and “next page” buttons. Although there are several different manufacturers, the underlying architecture, controls, and visual presentation are highly similar across different FMC CDU units.

The FMC CDU allows the pilot to input a desired route of flight, vertical profile, and speed profile. Route of flight information may be entered as waypoints (each flight is composed of a set of many waypoints) on the appropriate page of the FMC CDU via either manual keyboard entry or selection of pre-stored data base options via the line select keys adjacent to the display screen. Altitude constraints (either cruise altitude or a restriction to cross a horizontal waypoint or altitude at a given airspeed) may also be entered in the same manner. Aircraft speed may be controlled by either directly entering a speed value on the appropriate page, or by selecting a default speed profile (based on fuel economy or range considerations).

The Mode Control Panel (MCP)

The FMC CDU is not the only means by which the pilot can control aircraft speed, heading, and altitude. The MCP (see figure 5) allows the pilot to control autothrottle and autopilot modes, as well as to provide heading, altitude, air speed, and vertical speed targets to these systems. Autopilot and autothrottle modes are selected by depressing the appropriate buttons (e.g. LNAV (Lateral Navigation), VNAV (Vertical Navigation), FLCH (Flight Level Change), etc.), while airspeed, altitude, heading and vertical speed values are entered into the appropriate window via the associated selector knob. Although the distinction is not perfect, the FMC CDU is considered a "strategic" interface while the MCP is considered a "tactical" interface.[1] The FMC CDU is often used to implement actions that will take place or continue relatively far into the future (e.g. entering changes to the route of flight), while the MCP is often used to implement more immediate actions such as flying an assigned heading or climbing to a given altitude. Like the FMC, there are differences among manufacturers and models. However, at a conceptual level most MCP functions are very similar.



Mode Control Panel (MCP)

Figure 5 A Typical Mode Control Panel

In order to control aircraft performance via the MCP, the desired target(s) must be entered into the appropriate window(s), and the appropriate mode(s) must be selected. For example, in order to comply with the clearance “fly heading 180^{o}”, the pilot must set 180 in the heading window and select the heading mode by depressing the top of the heading selector knob. There is a significant degree of coupling between the FMC and MCP, as well as between autopilot modes. Some autopilot and autothrottle modes automatically activate other associated modes, while some information entered into the FMC will not be acted upon unless the appropriate autopilot mode is selected on the MCP. For example, LNAV (lateral navigation) and VNAV (vertical navigation) modes must be selected on the MCP in order for the autopilot to follow the horizontal and vertical guidance commands entered into the FMC. Additionally, in some cases system behavior depends on the values set in both the FMC and MCP. For example, when descending in the VNAV autopilot mode, the controlling altitude will be the highest of either the altitude set in the MCP or an altitude restriction set in the FMC.

Notes

[1] Billings, Charles E. *Aviation automation: The search for a human centered approach*. Mahwah, NJ: Lawrence Erlbaum Associates, 1997.

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