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Future Flight Decks

P. Douglas Arbuckle,
Kathy H. Abbott[†],
Terence S. Abbott,
and
Paul C. Schutte

*Mail Stop 102
NASA Langley Research Center
Hampton, Virginia 23681-0001
USA*

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[†]*On extended detail from NASA to FAA as National Resource Specialist, Flight Deck Human Factors*

E-mail
p.d.arbuckle@larc.nasa.gov

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P. Douglas Arbuckle, Kathy H. Abbott[†], Terence S. Abbott, and Paul C. Schutte
NASA Langley Research Center
Hampton, VA, USA

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Summary

The evolution of commercial transport flight deck configurations over the past 20-30 years and expected future developments are described.

Key factors in the aviation environment are identified that the authors expect will significantly affect flight deck designers. One of these is the requirement for commercial aviation accident rate reduction, which is probably required if global commercial aviation is to grow as projected. Other factors include the growing incrementalism in flight deck implementation, definition of future airspace operations, and expectations of a future pilot corps that will have grown up with computers.

Future flight deck developments are extrapolated from observable factors in the aviation environment, recent research results in the area of pilot-centered flight deck systems, and by considering expected advances in technology that are being driven by other than aviation requirements. The authors hypothesize that revolutionary flight deck configuration changes will be possible with development of human-centered flight deck design methodologies that take full advantage of commercial and/or entertainment-driven technologies.

Background and Assumptions

To provide a basis for discussions of future flight decks, it is important to understand why we need human operators in the commercial aviation system, how aviation safety is currently measured, the nature of aviation accidents, the evolution of commercial jet transport flight decks, and the factors involved in changing flight deck designs.

The Requirement for Human Operators

The airspace system is defined as the aircraft that are operating on the airport surface as well as in the air, the ground-based systems that provide supporting infrastructure, the human operators in both the aircraft and on the ground, and the procedures and rules for the human operators in the system. The airspace system has dynamic elements that are both continuous (aircraft flying) and discrete events (takeoff clearance). These continuous and discrete elements are numerous and interactive. A complete and accurate model of the entire airspace system has not yet been created and is not likely to be developed and validated for many years to come, if ever. Further complicating this situation is the fact that certain airspace

system variables, such as the weather, are beyond our ability to accurately predict.

For the above reasons, our current airspace system relies almost exclusively on humans as control elements. The control architecture of the airspace system is such that ground-based personnel are mostly located in the system outer loops and pilots are mostly located in the system inner loops. From the perspective of a control designer, the inability to model the airspace system with any reasonable degree of fidelity leads to the conclusion that an automatic control structure cannot be practically designed for the airspace system, given the desired levels of risk and cost. Given that full automation is not possible, a system containing both machine and human control elements will be required. It seems clear that it will be quite some time before fully automated aircraft are flying in commercial passenger service.

There is another reason that fully automated aircraft are not likely to provide commercial passenger service in foreseeable future. A fully automated aircraft would be designed and manufactured by humans. Since any aircraft is subject to human error right off the production line, the degree of automation is merely a choice among which humans can introduce error, not whether error occurs. At some level, a system is sufficiently complex that no single human can understand the entire design. This requires multiple humans to become involved in the design, with imperfect communication between humans becoming a major opportunity for error creation and propagation. Removing the human operator just puts the full burden of error on the designer and manufacturer. Even if the design and manufacturing were perfect, there is always the possibility that “the critical part” may not be installed or may be installed incorrectly during routine maintenance. The history of aviation is replete with examples of aircraft suffering failures that were never anticipated by the designers, but which became survivable due to human operator ingenuity. Although the aviation community has long believed that the humans in the aviation system prevented far more accidents than they caused, only recently have incident collection and analysis efforts begun to provide initial data that appear to validate this belief.⁽¹⁾

Aviation Safety -- the Accident Rate Plateau

Although technically we do not know how to measure safety with a single parameter, in discussions with the general public, the aviation industry generally uses “hull

loss” or “fatal” accident statistics for commercial jet transport aircraft. “Hull loss” is used by the industry to describe an accident where the aircraft is damaged beyond economical repair. Figure 1 shows the historic trends and probable trends in commercial aviation accidents. Hull loss accidents often result in fatalities and are almost always treated to extensive coverage in the local, if not worldwide, press. As can be seen from the figure, the accident rate has been essentially constant for at least 20 years. To the authors’ knowledge, the Boeing Company first drew public attention to the fact that if the accident rate remained constant, and airline traffic grew as they projected, then the number of hull loss accidents worldwide would reach almost one per week in the year 2015. This is now viewed by the aviation community as something that the public will not accept, implying a limited growth scenario for airline traffic unless something is done to reduce the hull loss or fatal accident rate.⁽²⁾

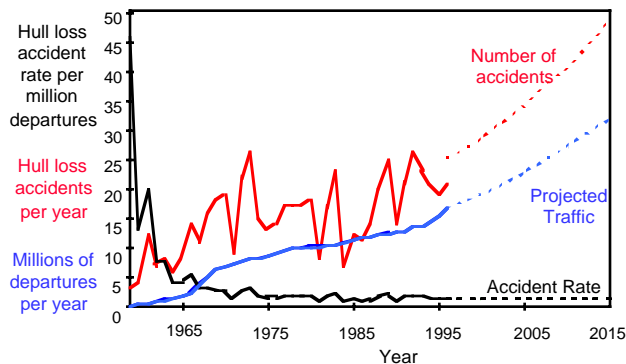


Figure 1 -- Global Commercial Airline Transport Safety Trends (data from Boeing)

The readily available statistics on hull loss or fatal accidents for large jet transports, general aviation and rotorcraft are reported by various sources.^(3,4) These sources gather information that varies according to factors such as the country in which the fatal accident occurred, the type of vehicle involved (large jet transport, general aviation, etc.), and the manufacturer of the aircraft (most commercial airline transport manufacturers have additional data on a fatal accident involving one of “their” aircraft). These statistics tend to be categorized according to “what happened” instead of “why it happened.”

Figure 2 shows a summary of primary cause factors for commercial airline transport hull loss accidents during the period 1987-1996. The percentages shown are based on the 71% of accidents during this period for which a “known cause” has been established and documented by the cognizant accident investigation authority. The primary cause factor distribution is essentially similar to that during the period 1959-1995. As has been the case during almost the last 40 years, the “flight crew” is listed as the prevalent primary cause factor in the commercial airline jet fleet. This is usually referred to as “pilot error.” A British study of accidents during 1980-1996 included turboprops and business jets, as well as accidents involving “Eastern-

built” aircraft during the period 1990-1996, and reached similar conclusions.⁽⁵⁾

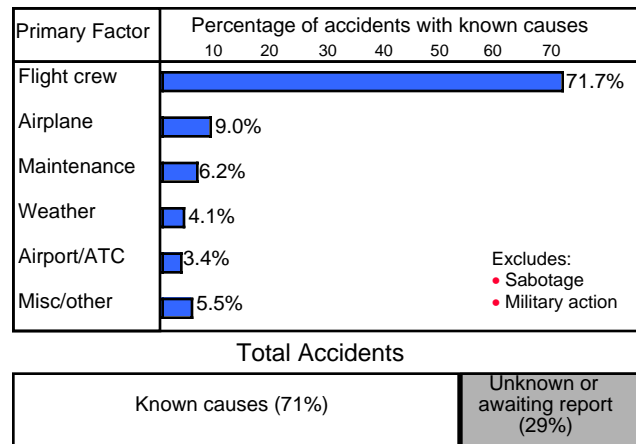


Figure 2 -- Primary Cause Factors for Global Commercial Jet Fleet Hull Loss Accidents, 1987-1996 (data from Boeing)

Most accident investigations that identify “pilot error” as a primary or major causal factor typically do not analyze why this error (or errors) occurred. This has happened in part because a conclusive analysis has often not been possible given the available data. Another factor is that the accident investigation authorities have historically been focused on identifying the specific sequence of events that resulted in the accident, with less attention on determining why each event occurred. Until very recently, “pilot error” was viewed as something that happened to the unlucky or incompetent, and most accident investigation authorities have not performed analyses of why “pilot error” occurs.

Unfortunately, the preponderant tendency for an accident investigation report to conclude by attributing the primary cause to “pilot error” has clouded the fact that there are almost always contributing causes from design, training, operations, maintenance, personal, and other factors.

There is also a tendency in many parts of the aviation industry to think that accident rate reductions can be obtained by changing training and procedures alone. This view does not appear to be supported by the evidence, since the global fatal accident rate is essentially unchanged for the last twenty years. If different training and procedures were the only answer, the authors believe the results would be more apparent in recent accident rate statistics than is the case.

Another argument that is often made for focusing on training and procedures versus design is the reality that changes in design will take longer to implement, and therefore, it will take longer to realize the benefits of new designs. The authors agree that any design changes, whether implemented in new aircraft or retrofitted, will take time to implement. However, if the desired improvements in aviation safety require design changes, then such changes must be pursued. This will be discussed again later in this paper.

A Model for Aviation Accidents

The FAA has presented a conceptual model for aviation accidents – a beam of light trying to pass through a box containing multiple rotating disks, where each disk contains a set of holes.⁽⁶⁾ As shown in Figure 3, when the holes on all of the disks are in alignment, the light beam passes through the box and comes out the other side, meaning an accident has occurred. This model captures the fact that in almost every accident, multiple events must occur in a certain combination to trigger the accident. This model also supports by implication the earlier assertion that the aviation system is non-deterministic and currently impossible to model in its totality.

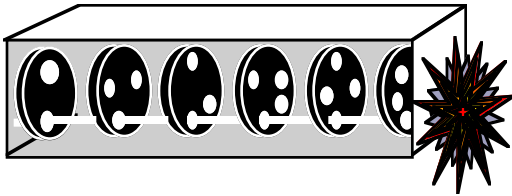


Figure 3 -- An Accident: The Holes in the Wheels Line Up

Given this model, there are three possible strategies for preventing a fatal accident. Figure 4 represents the first of these strategies – create a system, technology, or procedure to prevent an error/failure or series of errors/failures from resulting in an accident (“plug” holes in the last rotating disk). The second strategy is shown in Figure 5 – in this strategy, an overall system or set of procedures is designed to prevent a small error/failure from causing more serious problems (fill some holes in each of several rotating disks). This is also sometimes referred to as “catching the problem early” or “trapping errors.” Figure 6 portrays the third strategy, which involves implementing some new capability that prevents or significantly reduces the probability of a whole class of accidents (plug holes in the first rotating disk).

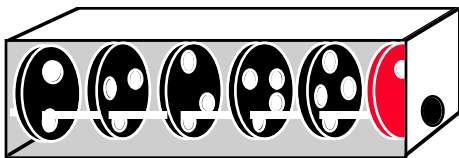


Figure 4 -- Prevention Strategy A: Mitigate Failure Effects

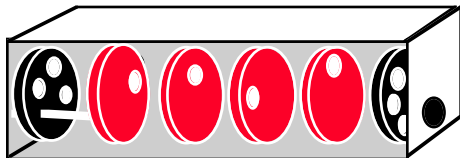


Figure 5 -- Prevention Strategy B: System Design to Minimize Failure Impacts or Propagation

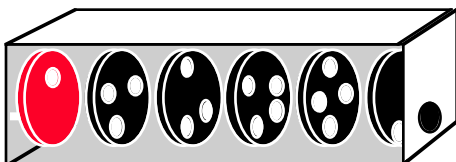


Figure 6 -- Prevention Strategy C: New Capability or Information to Eliminate Whole Categories of Accidents

Historically, the most prevalent strategy employed has been Prevention Strategy A. Prevention Strategy B is employed less often, and Prevention Strategy C is only rarely employed. It is a thesis of the authors that the industry has achieved much of the accident rate reduction that is possible from using Prevention Strategy A. Therefore, a more systems-oriented approach that includes Prevention Strategies B and C should be emphasized in the future if additional accident rate reduction is to be realized.

Commercial Transport Flight Deck Evolution

The commercial transport flight deck has evolved considerably since the first days of the Boeing B-707 and Douglas DC-8. In this discussion, flight decks are discussed as designed, even though the authors realize that many are operating today in modified form, having been retrofitted with various systems (GPWS, TCAS, etc.) that vary across the world. Retrofits are discussed later in the paper. Also in this discussion, the word “generation” is used to refer to a level of capability, not the point in time when the design was created. Finally, this section is written primarily from the flight crew’s perspective, not the design engineer’s perspective.

Even though it is not discussed, the flight deck evolution of business/regional jets and turboprops has generally followed the evolutionary path described below for large commercial transport aircraft flight decks.

The “classic” flight deck, which includes the above aircraft plus the B-727, the DC-10, and early series B-747, is relatively lacking in automation. A representative “classic” flight deck is shown in figure 7. All of these aircraft are characterized by the relative simplicity of their autopilot, which offers one or a few simple modes in each axis. In general, a single instrument indicates the parameter of a single sensor. In a few cases, such as the Horizontal Situation Indicator, a single instrument indicates the “raw” output of multiple sensors. Regardless, the crew is generally responsible for monitoring the various instruments and realizing when a parameter is out of range. A simple caution and warning system exists, but it covers only the most critical system failures.



Figure 7 -- Representative “Classic” Flight Deck (DC-10)

The first generation of “glass cockpit” flight decks, which include the B-757/767, A-310, and MD-88, receive their nickname due to their use of Cathode Ray Tubes (CRTs). A representative first generation “glass cockpit” flight deck is shown in figure 8. A mix of CRTs and instruments was used in this generation of flight deck, with instruments used for primary flight information such as airspeed and altitude. A key innovation in this flight deck was the “map display” and its coupling to the Flight Management System (FMS). This enabled the crew to program their flight plan into a computer and see their planned track along the ground, with associated waypoints, on the map display. Accompanying the introduction of the map display and FMS were more complex autopilots (added modes from the FMS and other requirements). This generation of aircraft also featured the introduction of an integrated Caution and Warning System, usually displayed in a center CRT with engine information. A major feature of this Caution and Warning System was that it prioritized alerts according a strict hierarchy of “warnings” (immediate crew action required), “cautions” (immediate crew awareness and future action required), and “advisories” (crew awareness and possible action required).⁽⁷⁾



Figure 8 -- Representative First Generation “Glass Cockpit” (B-757) Flight Deck

The second generation of “glass cockpit” flight decks, which include the B-747-400, A-320/330/340, F-70/100, MD-11, and B-777, are characterized by the prevalence of CRTs (or LCD’s in the case of the B-777) on the primary instrument panel. A representative second generation “glass cockpit” flight deck is shown in figure 9. CRT/LCD’s are used for all primary flight information, which is integrated on a few displays. In this generation of flight deck, there is some integration of the FMS and autopilot – certain pilot commands can be input into either the FMS or autopilot and automatically routed to the other.

There are varying levels of aircraft systems automation in this generation of flight deck. For example, the MD-11 fuel system can suffer certain failures and take corrective action – the crew is only notified if they must take some

action or if the failure affects aircraft performance. The caution and warning systems in this generation of flight decks are sometimes accompanied by synoptic displays that graphically indicate problems. Some of these flight decks feature fly-by-wire control systems – in the case of the A-320/330/340, this capability has allowed the manufacturer to tailor the control laws such that the flying qualities of these various size aircraft appear similar to pilots. The latest addition to this generation of flight deck, the B-777, has incorporated “cursor control” for certain displays, allowing the flight crew to use a touchpad to interact with “soft buttons” programmed on these displays. Another feature of the B-777 flight deck is a “closed-loop electronic check list” – this system senses control switch positions on the flight deck and automatically checks off the appropriate item on the checklist. This is in contrast to other available “open-loop electronic checklists” which require the flight crew to manually check off each item, even if they have already set the required control switch.



Figure 9 -- Representative Second Generation “Glass Cockpit” (A-320) Flight Deck

It is not clear when the next generation of large commercial transport flight decks will appear. Given the rate at which “new” large commercial transport aircraft are created, it could easily be a decade from now. However, it will occur, and there are a variety of possible forces and/or events that could precipitate the advance to the next generation. These will be discussed later in the paper.

Factors Influencing Flight Deck Design Changes

Flight deck changes in large commercial transports can be associated with new or derivative airplane programs, or can be introduced into existing aircraft in the form of retrofits. Typically, no change in a flight deck will be made unless there are new requirements or new objectives. The difference between requirements and objectives is subtle, nonetheless, it plays an important role in determining how flight decks are modified. Requirements must be met by new designs, objectives should be met if practical.⁽⁸⁾

The most significant changes in flight deck design are usually associated with a new airplane program or a derivative airplane program with significant operational or functional requirement changes, such as with the B-747-400 (the major requirement change being for operation by a two-person crew instead of the three-person crew of previous B-747's). However, new or derivative airplane programs do not always require significant flight deck changes.

Marketing requirements may have significant impact on flight deck changes: A derivative aircraft may not be marketable unless it has a common type rating with an earlier version, resulting in a requirement for the flight deck to be as similar to the previous flight deck as possible; conversely, a new aircraft may be more marketable if its flight deck is a basis for customers to choose the product.

Airlines can also require some update to the existing fleet, such as addition of a head-up display to obtain some operational advantage or improvement. Changes can also be mandated by regulation, such as the mandate for ground proximity warning systems (GPWS) or traffic alert and collision avoidance systems (TCAS).

“Certification risk” is lower if a new flight deck is similar to a previous one.⁽⁸⁾ “Precedence” is used as a basis for certifying many of the human factors aspects of flight decks.⁽⁹⁾ If the flight deck features are the same as or similar to a previous aircraft, or if the flight deck design results in equal or lower workload than a previously certified aircraft, then it is judged acceptable. A design that cannot be certified is a financial disaster for a commercial transport manufacturer. Uncertificable designs may be modified until they are acceptable to the certification authority, but this can be costly. The financial stakes associated with certification risk translate into the logical reality that such risks are not taken without substantive cause.

There is no incentive for manufacturers to change flight deck designs unless there are explicit requirements or benefits driving flight deck changes. Although requirements may imply fixed and uncompromised necessities, this is not always the case. For example, it is hard to imagine “aesthetically pleasing” as a requirement for flight deck design, but if customers indicate that this will be a factor in ordering aircraft, it may well become a requirement.

Design objectives may encompass many areas, including most of the advances in human factors, human-centered design, cognitive psychology, and cognitive engineering that have implications for flight deck design and flight crew performance and, by logical extension, aircraft safety. It is recognized that there may be changes to the design of flight decks that will increase automation usability, enhance flight crew situation awareness, and reduce pilot

errors, but they often are considered objectives. Further, some of these objectives suggest significant changes in flight deck designs, which, by default, conflict with requirements to keep future designs as similar to previous designs as possible. If an objective conflicts with a requirement, there is little doubt which will prevail.

Trends in the Aviation Environment

There are several trends that can be observed in aviation which will influence future flight deck designs. These include both flight deck trends and airspace system trends.

FAA Study on Flight Deck Issues

On April 26, 1994, an Airbus A300-600 operated by China Airlines crashed at Nagoya, Japan, killing 264 passengers and flight crew members. Contributing to the accident were conflicting actions taken by the flight crew and the airplane's autopilot. The crash provided a stark example of how a breakdown in the flight crew/automation interface can affect flight safety. Although this particular accident involved an A-300-600, other accidents, incidents, and safety indicators demonstrate that this problem is not confined to any one airplane type, airplane manufacturer, operator, or geographical region. This point was tragically demonstrated by the crash of a B-757 operated by American Airlines near Cali, Columbia on December 20, 1995, and a November 12, 1995 incident (very nearly a fatal accident) in which an American Airlines MD-80 descended below the minimum descent altitude on approach to Bradley International Airport, Connecticut, clipped the tops of trees, and landed short of the runway.

As a result of the Nagoya accident, as well as other incidents and accidents that appear to highlight difficulties in flight crews interacting with flight deck automation,⁽¹⁰⁾ the Transport Airplane Directorate of the FAA's Aircraft Certification Service launched a study in early 1995 to evaluate the flight crew/flight deck automation interfaces of current generation transport category airplanes. The study team included participants from the FAA, JAA (Joint Aviation Authorities), NASA, and a technical advisor from each of three universities in the United States.

The study team's report identified issues that show vulnerabilities in flight crew management of automation and situation awareness.⁽⁹⁾ Issues associated with flight crew management of automation included concerns about:

- Pilot understanding of the automation's capabilities, limitations, modes, and operating principles and techniques.
- Differing pilot decisions about the appropriate automation level to use or whether to turn the automation on/off when in unusual or non-normal situations. This may lead to potential mismatches

with the manufacturers' assumptions about how the flight crew will use the automation.

Flight crew situation awareness issues included vulnerabilities in, for example:

- Automation/mode awareness.
- Flight path awareness, including insufficient terrain awareness (sometimes involving loss of control or controlled flight into terrain) and energy awareness (especially low energy state).

The study team's report concluded that these vulnerabilities exist to varying degrees across the current fleet of transport category airplanes in the study, regardless of the manufacturer, the operator, or whether accidents have occurred in a particular airplane type. The team's report described a number of recommendations to address the vulnerabilities through changes in design, training and qualification, operations, and associated regulatory processes. Currently, many of these recommendations are being implemented.

Commercial Transport Flight Deck Trends

Most advances in flight deck capability since the advent of the first generation "glass cockpit" have been relatively evolutionary when assessed from an overall perspective. Some manufacturers would probably dispute this assertion as it applies to them. Airbus would mention differences between the A-310 and A-320, Boeing would cite differences between the B-757/767 and B-747-400, and McDonnell-Douglas would explain differences between the MD-80 and MD-11. Airbus and Boeing (which now includes the former McDonnell-Douglas) are justifiably proud of their products. However, both companies appear to spend some amount of their time defending their flight deck designs. In this competitive environment, certain major flight deck changes seem to be more difficult due to the apparent concern that such a change might constitute admission of a design weakness in a current product.

In the past, a disconcerting industry trend has been the proliferation of flight deck system automation paradigms. One advantage of industry consolidation is that half of the large transport aircraft manufacturers have been eliminated (Fokker and McDonnell-Douglas). Another favorable trend is that within the remaining companies there have been recent efforts to consolidate on one flight deck design philosophy. Airbus has maximum commonality among its current production aircraft (A-319/320/321, A-330, and A-340). Boeing has made significant progress in achieving commonality among the B-777, B-737-600/700/800, and B-757/767 follow-ons. However, at the moment, it appears that Airbus' automation philosophy is headed in one direction and Boeing's in the other. Is this appropriate for the industry? This question is being asked in public forums.⁽¹¹⁾ Also, earlier models from both companies, as well as Fokker and McDonnell-Douglas, do not have a flight deck automation approach consistent with the above mentioned aircraft, but they are still flying in airline

service and are expected to continue doing so for many years.

Another flight deck trend worth considering is the introduction of government-mandated flight deck "safety" systems, such as Windshear, Ground Proximity Warning System (GPWS), Traffic Collision Alerting System (TCAS), and others. The establishment of a regulation requiring these systems has typically been a governmental response to an accident investigation (or a series of investigations). Creating a flight deck system to provide a "last line of defense" warning to the crew of imminent danger is a prime example of accident Prevention Strategy A (see [A Model for Aviation Accidents](#)). In most cases, these systems are designed somewhat independently of a given aircraft's flight deck design and installed as a "retrofit" (from a design perspective, this is true whether the hardware is installed on a production line or in a maintenance hangar). The "integration" task in these cases is to ensure that the new system performs its intended function, while preventing it from interfering with the existing flight deck systems (or vice versa). This is different from a design approach where the system functionality is integral to the flight deck design. For retrofits involving a single new system, the focus of the certification authorities is typically on verifying that the system performs its intended function and doesn't interfere with the existing flight deck systems. For economic reasons, there is usually little interest in customizing the system implementation to each flight deck design. Therefore, over time, the flight deck designed by the manufacturer can be slowly "disintegrated" without the complete awareness of the manufacturer (who may not know about the retrofit), operator (who may not fully understand the flight deck design), or regulator (who is seeing each change separately over a long period of time).

Built to Last: Airframe versus Avionics

The lifespan of a modern commercial jet transport has unexpectedly affected the avionics implementation. With proper maintenance, the productive life of a modern commercial transport is approximately 30 years. In sharp contrast, the "technology lifespan" of computers and software in the last 15-20 years has been approximately 3 years. The first "glass cockpit" commercial transport aircraft were designed in the late 1970's, before the appearance of the personal computer; yet these aircraft are still being produced with an avionics architecture designed during that period. This architecture, now known as "federated," uses individual line replaceable units communicating with each other via dedicated, hard-wired interfaces. Such an architecture was never designed to have its functionality expanded easily – the paradigm at the time was that increased functionality would generally occur by replacing existing units, and only occasionally by adding new units and interfaces to the existing system.

The latest generation of Airbus and Boeing aircraft have more advanced avionics, with varying levels of avionics integration that translate into varying sophistication and use of databuses to move data within the avionics architecture. However, even the most integrated avionics on these aircraft have limited extendibility within functional limits defined by their designers. Therefore, during the 45-year life (30 year aircraft life plus 15 years in production) of this design, it is inevitable that some function not envisioned by the designer will be developed that cannot be easily incorporated into the avionics architecture – this has a direct bearing on the ease with which a given flight deck modification can be made.

A further point about the trend toward more integrated avionics is that current designs clearly indicate a focus on integration among the electronics and software rather than the functionality from the pilot perspective. A particular example is a modern transport aircraft where the autoflight “system” functions are hosted within the same avionics unit, yet the pilot must interface with what appears to be at least three different “systems,” placed in different flight deck locations. Potential reasons for this design choice include the desire to preserve “commonality” with flight decks in other aircraft manufactured by the company, and the avoidance of “certification risk” in proposing a new interface for the flight crew.

A final observation about trends in modern commercial jet transport flight decks is that, for reasons described above, the aviation industry is not keeping up with the rapid advances that are occurring in the broader industry that produces real-time, reliable computational systems. In a total reversal of the situation that existed 15 years ago, today the average commercial jet transport in airline service has more computing power and better human/computer interfaces in the hands of the passengers than in the hands of the flight crew. Given the disparity in time between commercial transport aircraft product cycles (on the order of a decade) and information technology product cycles (on the order of a year), it is inevitable that this trend will continue unless the aviation industry does something different.

In short, it seems apparent that the aviation industry must develop an approach to avionics architectures and flight deck design that enables integrated, extendible functionality from both the flight crew’s interaction level and at the engineering implementation level. A key feature of such an approach would be that “applications” (functions) with similar characteristics would have a common crew interaction paradigm. Another key feature of such an approach would be that the design allows new “applications” (functions) to be added after the product is fielded in service. This would be analogous to some of today’s personal computers.

Redefining “Retrofit”

An emerging trend could be the insertion of new flight deck systems and supporting avionics into an existing (or minimally modified) airframe design. The most extreme example of this known to the authors is the planned modification of several Federal Express DC-10’s into “MD-10’s.”⁽¹²⁾ This involves the conversion of the three-person DC-10 flight deck into a two-person MD-10 flight deck based on the MD-11 flight deck design and systems. The MD-10 project could be viewed as a “retrofit” and may pave the way for future modifications of this scope.

Such an approach may be a practical path to implementing future “new” flight deck designs that provide system-wide benefits. If such changes to an aircraft flight deck will yield significant improvements in both safety and operating economics, the likelihood of implementation will increase substantially.

Tomorrow’s Airspace System

The airspace system of the future is being “designed” today. Specifically, standards are being proposed by, and negotiated among, the various national aviation authorities, and the International Civil Aviation Organization (ICAO). The future airspace system is aimed at providing increased operational efficiencies for users of the airspace system, while preserving or enhancing existing safety and capacity levels.

The CNS/ATM concept is a new paradigm for the architecture and operation of the airspace system, as illustrated in figure 10. Inherent in the successful implementation of CNS/ATM concepts is the idea that operational access and constraints are explicitly based on performance. This necessitates an explicit linkage between separation criteria and Required System Performance (RSP). RSP is used to define a “protected volume” around each aircraft based on its RSP – a higher level of RSP equates to the need for a smaller protected volume (which allows closer separation). This concept allows users to make explicit investment decisions vis-à-vis the aircraft-by-aircraft RSP they need to meet their operational requirements.

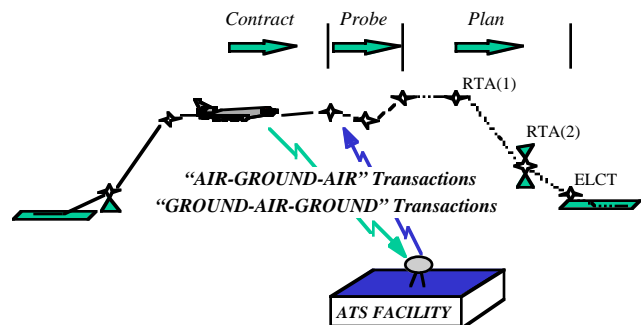


Figure 10 -- Future Airspace System Operational Concept

RSP is a combination of Required Communications Performance (RCP), Required Navigation Performance (RNP), and Required Monitoring Performance (RMP). RNP indicates how well a given airplane knows where it is and adheres to a defined flight path.⁽¹³⁾ RMP indicates the accuracy of the information about positions, velocities, and accelerations of a set of aircraft in the airspace system. RCP indicates the message capacity, integrity, and time delay between initiation and its receipt at the intended location.

The impact that different RSP levels will have on commercial transport flight decks is not easy to predict. The inherent “control structure” of today’s airspace system, described earlier, is such that ground-based personnel are mostly in the system outer loops and pilots are mostly in the system inner loops. As in any control system, information must flow between the inner and outer loops for the overall system to work. The humans in today’s system provide a large measure of this connectivity. It is not clear if the current “control structure” will provide the desired levels of RSP. It is also not clear how airspace system users will rely on airspace system providers to achieve a given level of RSP. One possible outcome is that more air traffic management functions (including separation) may be performed by the flight crew. Figure 11 shows an example approach for how this might occur, with varying information available and activities occurring based on different system element dynamics.

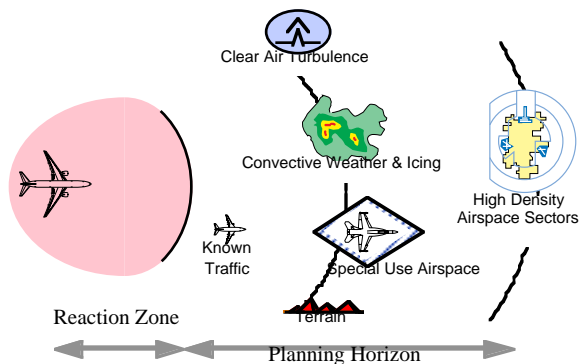


Figure 11 -- An Approach for Flight Deck Involvement in Air Traffic Management

Trends in the Global Environment

There are several trends that can be observed in the broader marketplace that are likely to be major influences in future flight decks.

Demographics of the Pilot Population

Demographically, an entire generation of people who have grown up with the personal computer are about to reach the job market. The pilots of this generation are not “intimidated” by computers and have high expectations with regard to the ease of use of their computer. The

authors postulate that this generation of pilots will not view the interfaces in today’s “modern” flight deck as acceptable; already today’s computer-literate pilots view the FMS Control Display Unit (CDU), with its alphabetically- ordered keypad and primitive interface, as hopelessly antiquated and awkward to use.

Another demographic trend (at least, in the United States) is the percentage of current airline pilots who were trained to fly by the military. This trend has been slowly at work for years, but has accelerated in the post-Cold War era. The downsized military has needed to train few new pilots. Over time, this has resulted in a minuscule pool of military pilots for the airlines to hire. Yet the airlines’ requirements for pilots have grown with the size of the fleet (which has doubled worldwide in the last 20 years). The “Age 60” rule guarantees that the large number of US airline pilots who served in the military during the Vietnam War are on the verge of retirement. Replacing these pilots will lead to a larger number of “low-time” (relative to today) pilots operating sophisticated aircraft. Also, the airline pilot population will become less homogeneous as the number of former military pilots, united by their common (and relatively extensive) training experience, declines.

“Revolutionary” Technologies

There are several “revolutionary” technologies whose development is being driven by one or more broad commercial markets.

Speech recognition has been pursued for decades, but only limited functionality is currently available on the market and many of these products are notorious for becoming nonfunctional in the presence of moderate background sounds and noise. However, the pace of development in this area is apparent by the progress seen in products for personal computers. The authors believe that inexpensive and robust speech recognition capabilities are only years away. This technology, implemented properly, could significantly alter human/computer interactions in the flight deck.

Eyeglass-based displays technology is another “revolutionary” technology whose development is being driven by a commercial market much bigger and broader than aviation. In this case, the “market pull” is the entertainment and gaming industry. While today’s gaming devices are completely unsuitable for a flight deck application, one can imagine a device the size of ordinary eyeglasses, able to project images into the eye that appear superimposed on the outside scene in a manner analogous to the Heads Up Displays (HUD’s) found in all modern military aircraft. The capability to project, in a conformal manner superimposed over the pilot’s out-the-window view, the position of terrain, traffic and weather, would have significant implications for current flight deck systems, interfaces and configuration.

The authors believe that requirements to incorporate new technologies (such as those described above) developed “outside” the aviation community, combined with the environmental trends previously described, will contribute to the need for new flight deck designs.

Human-Centered Flight Deck Design

Because advanced aircraft are, and will continue to be, so heavily automated due to demands for efficiency and safety, and given the problems that have been noted in current flight decks,^(9,10,14,15) it seems apparent that a new approach should be considered. This approach is becoming known as human-centered flight deck design. Human-centered flight deck design is primarily a ‘systems’ approach to design of the ‘interface’ between the pilot and aircraft (i.e., the flight deck). The approach has also been referred to as a ‘top-down,’ requirements-driven methodology, where the requirements are formulated hierarchically from mission objectives and more extensively include human performance considerations. This approach can be used to design new flight decks or to retrofit existing flight deck designs.

Human-centered flight deck design allows multiple design concepts, including “radical” ones.⁽¹⁶⁾ Human-centered flight deck design is a Prevention Strategy B, though a resulting flight deck implementation could be viewed as a Prevention Strategy C (see [A Model for Aviation Accidents](#)). The elements of human-centered flight deck design are described below.

Human-Centered Design Principles

The basic tenet of human-centered design principles is that, “The Human Operator Must Be in Command.”⁽¹⁷⁾ In an aircraft, this means the pilot shall always be in command, even when using automation. Thus, automation, including air traffic management automation, must never remove the pilots from the command role, either implicitly or explicitly. Command entails both authority and awareness. Reference (17) stresses the need for appropriate pilot involvement in, information about, and comprehension of the tasks being performed. While it is tempting to view this as strictly an interface problem, closer examination reveals that it is a systems problem. Information and format can assist in making complexity understandable, but it will not be as effective as reducing complexity. Likewise, displaying information about system status may assist the pilot in recognizing modes, but designing a system with only immediate and pilot-commanded mode changes should provide better awareness. Thus human-centered design starts at the overall function definition and allocation level rather than the interface level. The design should be based on a human-centered design philosophy and should reflect both the mission goals and the pilots’ roles.

Design Philosophy

A human-centered flight deck design philosophy has been developed at NASA Langley Research Center.⁽¹⁸⁾ This philosophy is expressed as a set of guiding design principles, and is accompanied by information that will help focus attention on flight crew issues earlier and more systematically in the design process.

The philosophy assumes that the flight crew will remain an integral component of the flight deck for the foreseeable future (see [The Requirement for Human Operators](#)). The philosophy seeks to elevate design issues associated with the understanding of human performance and interaction with automation to the same level of importance as the historical focus on technological issues, such as hardware performance and reliability. Moreover, it considers the importance of optimizing the combined flight crew/flight deck system performance above any single component of the total system. It also seeks to elevate flight crew and flight deck issues to the same level of importance given other aircraft design disciplines, such as aerodynamics and structures. The philosophy includes the view that flight deck automation should always support various pilot roles in successfully completing the mission. These roles are: pilots as team members; pilots as commanders; pilots as individual operators; and, pilots as flight deck occupants.

Function Allocation and Involvement

Function allocation is an important element of flight deck design. It is at the heart of human-centered flight deck design. The following function allocation guideline is distilled from references (17) and (18): The pilot should, in general, be more involved in actions and decisions that have significant consequences on the overall mission, and be less involved in actions and decisions that are relatively deterministic, time constrained, tedious or repetitious, or require great precision.

The purpose of involvement is to engage the pilot in the task. The purpose of engagement is to increase pilot situation awareness. When engagement is low due to factors such as boredom, complacency, or fatigue, the pilot enters a state described as a hazardous state of awareness.⁽¹⁹⁾ One way these hazardous states of awareness may be identified is based on electroencephalogram (EEG) signals and other physiological indices. The model for predicting whether the flight crew will experience inappropriate or hazardous states of awareness involves three sets of factors: predisposing, inducing, and counteracting.⁽¹⁹⁾

Examples of predisposing factors are how likely the individual is to become complacent, bored, or absorbed. Examples of inducing factors are sensory restriction (such as monotony) and stressor preoccupation from life situations. The model hypothesizes that counteracting factors negate or prevent the effects of the predisposing and inducing factors for hazardous states. Examples of

counteracting factors are attentional competence, communication flow, and task engagement.

Reference (20) describes a system which measures mental task engagement. Because human/automation task allocation strongly influences task engagement, this engagement index may be used to evaluate various function allocation schemes for their influence on task engagement.

Flight Deck Mission Categories

Reference (21) proposes combining human-centered design principles with a systems-oriented approach to designing new flight decks which will meet overall mission requirements. It is hypothesized that this will reduce system integration problems. This approach requires that mission requirements are defined before any designing of the flight deck or other aircraft systems occur.

In Reference (21), a mission goal is assumed for an aircraft to be that of moving “passengers and cargo from airport gate to airport gate safely and efficiently.” The overall function of the flight deck systems is assumed to be that of managing the mission of the aircraft. Both normal and abnormal situations are considered for accomplishing the mission. Four levels of mission management are defined: flight management, communications management, systems management, and task management. Although similar to the traditional pilot functions of aviate, navigate, and communicate, these categories are from the total flight deck perspective, rather than from just the pilot’s. The interactions among these functions create blended tasks for the flight crew.

One of the design principles from reference (17) indicates that the behavior and purpose of the automation should be clear to the user. Thus, information relevant to the blended task should be presented to the flight crew, and in such a way that the underlying function(s) or relationships are transparent to the flight crew. An example of how to do this is presented below.

Task-Oriented Display Design

Reference (22) describes the development of a display design process using a function allocation that decomposes “the user’s task only to a level where relevant information can be identified” as opposed to where a data source could be identified. This “relevant information” may or may not be raw data, and can be synthesized from underlying data. The “relevant information” is presented in such a form as to be more appropriate for the task.

This task-oriented design process was applied to develop an aircraft engine display. In a simulation evaluation, pilots had better performance than with a traditional display – the pilots also preferred the task-oriented display. This particular display was for the control of engine thrust and the monitoring of engine health. Rather than provide

individual pieces of information which the pilot had to mentally combine (a task ill suited for humans and not directly related to the task), the display presented the information after it was combined. The synthesized information was presented in a form that was more appropriate for the pilot’s task. The key to successfully using this function allocation process is understanding the real task the user or flight crew must perform.⁽²²⁾

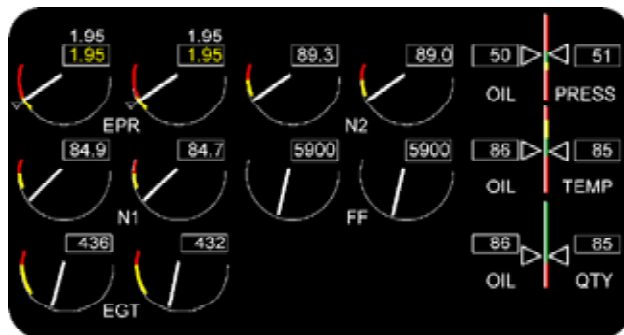


Figure 12 -- Erroneous Engine Pressure Ratio (EPR) Information, Traditional Engine Display

Figure 12 shows a traditional engine display, and the task-oriented engine display is shown in figure 13. Both displays depict an identical scenario, which is similar to the 1982 Air Florida accident. In this scenario, the Engine Pressure Ratio (EPR) information is erroneously high during a takeoff task – the result is that the pilots may think they have set takeoff power, when in fact they have not. Figure 13 clearly shows the advantage of the task-oriented display in displaying a problem with takeoff power selection (the difference between the white and yellow bars on the left side). The task-oriented engine display also shows that both engine temperature (EGT) and fuel flow (FF) are much too low for the amount of power the engine is supposedly producing.⁽²²⁾

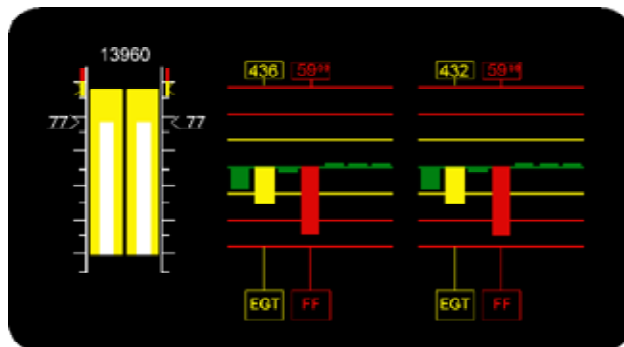


Figure 13 -- Erroneous Engine Pressure Ratio (EPR) Information, Task-Oriented Engine Display

Fault Management

The use of automation and the complexity of aircraft systems in general has increased as technologies have matured. However, as complexity increases, so does the difficulty of recognizing, anticipating, and preventing system errors. The presence of these difficulties is called “brittleness.”^(17,23) To control the effect of brittleness, most

systems require a human to be incorporated in the system. This places the human in the unique role of troubleshooter and the last defense.

This approach has been identified as having human/system performance vulnerabilities, especially in the flight deck. Reference (24) points out that the response to human performance issues in a complex automated system, such as a flight deck, has not kept up with the application of automation, so that these issues are only surfaced when accidents or incidents occur. One reason for having humans on the flight deck is to deal with problems, contingencies, or failures. Yet, the flight deck design, supporting training, and procedures, do not readily address this flight crew function. Flight crews are primarily provided training for normal operation and anticipated failures. If a failure is novel (unanticipated), the flight crew may not respond properly,⁽²⁵⁾ as supported by the number of inappropriate crew responses to failures; however, responding to novel failures is an accepted part of the flight crew's job.

Reference (26) presents a framework for real-time fault management that integrates three elements:

- *operational levels* – which are the aircraft mission, the physical aircraft in an aerodynamic environment, and the aircraft systems;
- *cognitive levels of control* – which are defined as skill-based, rule-based, and knowledge-based behaviors; and,
- *operational fault management tasks* – which are detection, diagnosis, prognosis, and compensation.

The combination of all these factors describe crucial fault management issues which should be reviewed in any flight deck design.

Likely Future Flight Deck Elements

We do not know for certain what the flight decks of the future will look like, nor how they will function. However, the authors believe that future flight decks will contain at least some of the following elements:

- Sidestick control inceptors, interconnected and with tailorable force/feel, preferably “backdriven” during autopilot engagement
- “Mode-less” flight path management
- Display area filled with large, high resolution displays having multiple signal sources (computer-generated and video)
- Graphical interfaces for appropriate flight deck systems
- High-bandwidth, two-way datalink communication capability embedded in appropriate flight deck systems
- Voice interfaces for appropriate flight deck systems
- Modular avionics architectures designed to be upgraded every 5-10 years, with both new hardware (processor, memory, storage) and new software (“applications” and “operating system”)

In the longer term, it is possible that future flight decks will also include glasses-mounted displays that enable “virtual environment” presentations of traffic, weather, terrain, etc.

Market Prospects for Flight Deck Innovation

Although this paper has concentrated on commercial jet transport flight decks, there are opportunities for flight deck innovation that span the entire aviation industry.

The single engine general aviation market is a significant opportunity for flight deck innovation. Flight deck designs that are significantly easier to operate than historical designs could reduce barriers to entry (both initial training and ownership), thereby significantly expanding the market potential of this segment. One vision for this segment is an aircraft with operating capability and costs that are commensurate with luxury automobiles.

The multi-engine corporate airplane market is another significant opportunity for flight deck innovation. The authors contend that the aircraft in this market segment already include some of the most sophisticated flight deck capabilities in the world. Given that most corporate operators lack a large fleet or pilot workforce, there are far fewer training barriers to adoption of new technology and new systems in these aircraft. This segment also has a high historic interest in obtaining the latest avionics capabilities and improving safety. The substantial resources available in this segment, coupled with the above factors, appears to make this segment the most open to ‘revolutionary’ improvements in flight deck design. This is evidenced by the development of advanced flight deck avionics suites, such as Honeywell’s *Primus Epic*TM.

The commuter airline segment wants to lower its accident rate to become “as safe” as the major airlines. This need is made more complex by the relative inexperience of the average commuter airline pilot. However, many of the aircraft used in commuter airline service use the same avionics suites as the multi-engine corporate segment; therefore, leverage is possible.

Interestingly, today’s subsonic commercial jet transport segment has the least apparent requirement for flight deck innovation. Vulnerabilities exist, but commercial jet transports are generally the safest form of aviation transportation available. However, as the airspace systems transitions to future operational environments, opportunities for flight deck innovation will present themselves. Also, if another aviation market segment takes the “certification risk” and develops a new and successful flight deck design approach, it is possible that commercial jet transports will adopt it.

Looking toward the future, the potential emergence of economic supersonic commercial jet transports, if realized, would present flight deck innovation opportunities. NASA

studies to date have shown that unique vehicle/operational requirements will require flight deck solutions that differ significantly from today's subsonic transport aircraft.

Concluding Remarks

The demand for commercial aviation accident rate reduction will be relentless, since accident rate reduction will be required to realize the projected growth in global aviation. Since "pilot error" continues to be cited as a major factor in the majority of accidents, it will receive attention leading to the realization that the needed safety improvements cannot be accomplished with procedural and training changes alone. Computer and communication technologies will be created by the demands of the broader commercial market – these technologies will have significant potential in aviation applications. Human-centered flight deck design methodologies will be applied to produce a lasting (and perhaps singular) human-centered systems framework that will be used as a basis for modifying flight deck implementations as technologies evolve or become available for use. It is too early to tell, but we may be near the threshold of a 'revolution' that leads to significant changes in flight deck systems and how pilots interact with them.

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