SUMMARY OF A CREW-CENTERED FLIGHT DECK DESIGN PHILOSOPHY FOR HIGH-SPEED CIVIL TRANSPORT (HSCT) AIRCRAFT

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INTRODUCTION

Past flight deck design practices used within the U.S. commercial transport aircraft industry have been highly successful in producing safe and efficient aircraft. However, recent advances in automation have changed the way pilots operate aircraft, and these changes make it necessary to reconsider overall flight deck design. Automated systems have become more complex and numerous, and often their inner functioning is partially or fully opaque to the flight crew. Recent accidents and incidents involving autoflight system mode awareness (Dornheim, 1995) are an example. This increase in complexity raises pilot concerns about the trustworthiness of automation, and makes it difficult for the crew to be aware of all the intricacies of operation that may impact safe flight. While pilots remain ultimately responsible for mission success, performance of flight deck tasks has been more widely distributed across human and automated resources. Advances in sensor and data integration technologies now make far more information available than may be prudent to present to the flight crew.

The proposed High Speed Civil Transport (HSCT) will likely add new automated systems, even more automation complexity, and new flight crew information requirements. For example, an external vision system, which would combine sensor and data base information to compensate for the absence of forward windows in the flight deck, may include a variety of options for minification/magnification, sensor selection, aim point, decluttering, automatic alerting, system enhancement of sensed objects for better detection, eye points (map view vs. perspective view), and synthetic flight path guidance and other enhanced symbology. This can add tremendous complexity and information overload from the pilot's perspective. In addition, there are dozens of new flight deck requirements that could create new flight crew monitoring and interaction tasks, such as laminar flow status, high-lift system configuration, radiation monitoring, sonic boom management, center of gravity management and supersonic/subsonic speed management. The related demands on the flight crew could impact workload, situation awareness, and information management. Design issues concerning flight crew authority, function allocation, and the role of the flight crew and automated systems will also be magnified, because current HSCT concepts may require mandatory use of autothrottles for landing and automatic control of other flight control surfaces to successfully implement flight envelope protection.

Consequently, whether one is concerned with the design of the HSCT, or a next generation subsonic aircraft that will include technological leaps in automated systems, basic issues in human usability of complex systems will be magnified. These concerns must be addressed, in part, with an explicit, written design philosophy focusing on human performance and systems operability in the context of the overall flight crew/flight deck system (i.e., a crew-centered philosophy). This document provides such a philosophy, expressed as a set of guiding design principles, and accompanied by information that will help focus attention on flight crew issues earlier and iteratively within the design process.

The philosophy assumes that the flight crew will remain an integral component of safe and efficient commercial flight for the foreseeable future because human skills, knowledge, and flexibility are required in the operation of complex systems in an unpredictable and dynamic environment. The performance of the overall flight crew/flight deck system depends on understanding the total system, its human and automated components, and the way these components interact to accomplish the mission. The philosophy, therefore, seeks to elevate design issues associated with the understanding of human performance and cooperative performance of humans and automation to the same level of importance as the past focus on purely technological issues, such as hardware performance and reliability. It also seeks to elevate flight crew/flight deck issues to the same level of importance given other aircraft design areas, such as aerodynamics and structural engineering. The philosophy includes the view that flight deck automation should always support various pilot roles in successfully completing the mission. Pilot roles can be defined in many ways, but the philosophy suggests that it is important to identify human roles which highlight and distinguish important categories of design issues that can affect overall flight crew/flight deck performance. The roles defined here are: pilots as team members, pilots as commanders, pilots as individual operators, and pilots as flight deck occupants. The role of team member highlights design issues that affect communication, coordination, common functional understanding and resource management. The role of commander highlights design issues that affect authority, responsibility and the allocation of functions. The role of individual operator highlights traditional human factors design issues such as workload, anthropometrics, task compatibility with human strengths and limitations, and interface design. The role of occupant highlights design issues such as comfort, health, safety, and subsistence. Design principles are presented according to these pilot roles.

The full philosophy document (Palmer, Rogers, Press, Latorella, & Abbott, 1995), of which this conference paper is a brief overview, is Part 1 of a two-part set. The objective of Part 1 is to provide a description of the philosophy at a level that is aimed primarily toward design team managers. It is intended to: (1) establish a common perspective of crew-centered design, and the ways that perspective can be applied within the design process; and (2) provide a framework for organizing increasingly detailed flight deck guidelines which are consistent with the principles and philosophy statements. Part 2 of the document set will provide more detailed information on relevant design guidelines, test and evaluation issues, recommendations for how to apply the philosophy, and methods for identifying and resolving conflicts among design principles and among design guidelines.

The authors wish to acknowledge the substantial contributions of the many participants involved in the development and review of the philosophy, including researchers at NASA Langley, NASA Ames, Boeing Commercial Airplane Group, McDonnell-Douglas Aerospace-West, and Honeywell.

DESIGN PROCESS

The process by which commercial flight decks are designed is complex, largely unwritten, variable, and non-standard. The process is also strongly reliant on the knowledge and experiences of individuals involved in each program, which has meant that the application of any philosophy to the design process has been necessarily informal. That said, Figure 1 is an attempt to describe the design process and where we believe the philosophy should have an impact. Although Figure 1 is not intended to exactly represent the accepted design process within any particular organization or program, it represents (except for the application of the philosophy) a composite flight deck design process based on various design process materials that have been generated within or provided to NASA's High-Speed Research (HSR) program, and is meant to be descriptive of accepted design practice. The philosophy and its impact are shown with double lines to illustrate that this is prescriptive information based on the views of the authors.

Some very important points need to be made about where the philosophy affects the design process. First, the philosophy should affect any step or stage of the design process where design decisions are made. Second, although the philosophy is most commonly applied to "how to" decisions in selecting design concepts that meet various requirements (i.e., the boxes labeled “Initial Design Concepts” and “Final Integrated Design”), crew issues can also affect the "what" of design, that is, what the aircraft or the flight deck must do, operationally or functionally. While the number of crew issues that can affect the operational and functional "what" may be small compared to those that affect the "how to," especially at the aircraft level, they are important (especially those concerning the pilot role of occupant). It is also important to note that we believe the philosophy has implications for the design process itself. For example, the philosophy emphasizes that total flight crew/flight deck performance is more important than performance of individual components, suggesting that flight deck integration issues should be addressed prior to, or in parallel with, development of individual flight deck systems or components (e.g., synthetic vision system for the HSCT). This is contrary to the way flight decks are traditionally designed, though we recognize that the inclusion of integration issues before systems are completely specified may be difficult.

Also, while the philosophy is currently limited to principles addressing the flight deck as a product of design, it could also include principles of the design process. For example, we could easily envision a principle stating that flight deck design, particularly issues pertaining to flight crew operability, should be addressed as early as possible and with as many resources as other aircraft design areas, such as propulsion, structures, and noise.

THE PHILOSOPHY

The crew-centered flight deck design philosophy presented here begins with the explicit acknowledgment that the flight crew, flight deck, and even the airplane itself are only parts of a much larger commercial air transportation system. Other elements of this system include the airlines and their flight dispatchers and maintenance personnel, weather forecasters, airport operators, air traffic controllers, and government regulators. Mission success is the overall goal, and it depends upon the cooperation and performance of each of these elements. Within this context, however, the philosophy contained in this document is limited to the operation of the aircraft by the flight crew. Because human skills, knowledge and flexibility will continue to be required to operate complex systems in the dynamic and often unpredictable aviation environment, flight deck design should be crew-centered in the sense that it should support the flight crew in successfully accomplishing the mission.

The crew-centered design philosophy espoused here can be described in its simplest form with the following set of Philosophy Statements, numbered as S-1 through S-3:

S-1. Each design decision should consider overall flight safety and efficiency. Combined flight crew/flight deck system performance is more important than local optimization of the performance of any human or automated component in that system.

S-2. Overall flight crew/flight deck performance and the performance of the human and automated components are affected by qualitatively different sets of issues depending on the specific operational roles in which pilots are viewed. Flight deck design should consider these different roles.

S-3. Humans and machines are not comparable, they are complementary (Jordan, 1963); that is, they possess different capabilities, limitations, strengths and weaknesses, and there is a mutual dependence required between humans and machines to successfully accomplish the mission. Safety and efficiency of flight will be maximized by focusing on ways to develop and support the complementary nature of the flight crew and the flight deck systems.

This philosophy presented in the above statements is discussed in the following sections, in terms of pilot and automation roles, design principles, and issues related to resolving conflicts among the principles. The organization of the principles is determined by the various roles of the flight crew members, as described below. The pilot roles also influence the organization of the categories of design guidance, as described in Palmer, et al. (1995).

<u>Pilot Roles</u>

The organizing scheme used for the generation and presentation of the principles is based upon the role of pilots as team members, commanders, individual operators, and flight deck occupants. These roles are nested rather than independent. That is, the pilot is always an occupant, and is an operator while in the roles of commander and team player. Thus, there will be some overlap in design issues related to the different roles. But we believe these roles highlight and distinguish important categories of design issues that can affect human performance and overall flight crew/flight deck performance.

With the complex systems, technologies, and operating environments that characterize modern commercial aviation, how humans work with other "agents," human and automated, (e.g., in communicating, coordinating, and sharing functions) is a major design issue. Cockpit Resource Management (CRM) evolved from the realization that problems in communication and coordination among crew members contributed to a large number of accidents and incidents. Problems of communication and coordination do not only occur between crew members; miscommunications between flight crew and air traffic controllers have been well documented in Aviation Safety Reporting System incident reports. Further, automation "surprises" reflecting pilot misunderstanding of automated systems such as the flight management system and autopilot system are well documented (Sarter & Woods, 1992). The team member role addresses these issues. While authority issues and the role of commander could be covered under the role of team member, we felt it was important to call it out separately because of the significance of authority issues in defining the human-centered philosophy. There is strong consensus that the pilot will continue to be ultimately responsible for safe operation of the aircraft (e.g., Billings, 1991; Wilson & Fadden, 1991), and this should be a primary driver of function allocation decisions. Supporting the pilot as an individual operator is the primary focus of most current human factors guidance -- design must account for all that is known about how humans perform tasks. The role of occupant was defined separately because it is easy to forget that the design must support the pilot in more than the obvious mission functions; there are peripheral tasks and pilot needs that must be supported in the context of the pilot as a human occupying a specific environment for a period of time. Each of these roles is described below:

> *Pilots as Team Members*: This reflects the role of pilots as members of a team that includes not only the other flight crew members, but also elements of the flight deck automation, and in the larger context, elements of a distributed system including air traffic controllers, airline dispatch, regulatory agencies, etc. The issues involved include the need for communication, coordination, and shared functional understanding among all team members to successfully accomplish tasks.
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> *Pilots as Commanders*: This reflects the role of each pilot, individually, as being directly responsible for the success of the mission. The issues involved include the level of pilot authority over the flight deck automation, and the ability of the pilot to delegate tasks.
>
> *Pilots as Individual Operators*: This reflects the role of pilots as individual human operators working within a complex system of controls and displays. The issues involved include many of the traditional human factors disciplines such as anthropometrics, control/display compatibility, and cognitive processing.
>
> *Pilots as Occupants*: This reflects the role of the pilots as living organisms within the flight deck environment. The issues involved include ingress and egress capability, protection from the radiation and atmospheric conditions at the expected cruise altitudes, and accommodation of items such as food and drink containers.

We believe that these roles represent distinctly different design concerns and issues. A major benefit of organizing the guiding principles according to the pilot roles identified above is that it serves as a bridge into the supporting research literature on human factors and flight deck design. The pilot roles also serve as one of the dimensions by which the design guidelines are categorized.

<u>Automation Roles</u>

As stated earlier, the philosophy suggests that overall performance of the flight crew/flight deck system is best served by prescribing that the sole purpose of automation is to support specific roles of the flight crew in accomplishing the mission. In this sense, the automation is always subservient to the flight crew. It may substitute for the pilot entirely in conducting some functions and tasks, it may augment the pilot by performing certain control actions, or it may aid the pilot in the gathering and integration of information.

<u>Design Principles</u>

A fundamental purpose of constructing a set of principles to represent a philosophy, is for these principles to serve as practical guides and not merely abstract concepts. This document therefore strives to present the principles in a form that will result in consistent interpretations, even though this may result in less elegance in phrasing. The principles are listed below according to the pilot roles described above, and are numbered as PT-x, PC-x, PI-x, or PO-x, for principles related to the roles of team member (PT), commander (PC), individual operator (PI), or flight deck occupant (PO).

<u>Pilots as Team Members</u>

PT-1. The design should facilitate human operator awareness of his or her responsibilities, and the responsibilities of the other human operators and automated flight deck systems, in fulfilling the current mission objectives.

PT-2. The design should facilitate the communication of activities, task status, conceptual models, and current mission goals among the human operators and automated flight deck systems.

PT-3. The design should support the dynamic allocation of functions and tasks among multiple human operators and automated flight deck systems.

PT-4. The design should assure that team limitations are not exceeded.

PT-5. Cooperative team capabilities (e.g. use of collective resources and cooperative problem solving) should be used to advantage when necessary.

PT-6. The design should minimize interference among functions or tasks which may be performed concurrently by multiple human operators or automated flight deck systems.

PT-7. The design should facilitate the prevention, tolerance, detection, and correction of both human and system errors, using the capabilities of the human operators and the flight deck automation.

Pilots as Commanders

PC-1. The human operator should have final authority over all critical flight functions and tasks.

PC-2. The human operator should have access to all available information concerning the status of the aircraft, its systems, and the progress of the flight.

PC-3. The human operator should have final authority over all dynamic function and task allocation.

PC-4. The human operator should have the authority to exceed known system limitations when necessary to maintain the safety of the flight.

Pilots as Individual Operators

PI-1. The human operator should be appropriately involved in all functions and tasks which have been allocated to him or her.

PI-2. Different strategies should be supported for meeting mission objectives.

PI-3. The content and level of integration of information provided to the human operator should be appropriate for the functions and tasks being performed and the level of aiding or automation being used.

PI-4. Methods for accomplishing all flight crew functions and tasks should be consistent with mission objectives.

PI-5. Procedures and tasks with common components or goals should be performed in a consistent manner across systems and mission objectives.

PI-6. Procedures and tasks with different components or goals should be distinct across systems and mission objectives.

PI-7. The design should facilitate the development by the human operator of conceptual models of the mission objectives and system functions that are both useful and consistent with reality.

PI-8. Fundamental human limitations (e.g., memory, computation, attention, decision-making biases, task timesharing) should not be exceeded.

PI-9. Fundamental human capabilities (e.g., problem solving, inductive reasoning) should be used to advantage.

PI-10. Interference among functions or tasks which an operator may perform concurrently should be minimized.

Pilots as Flight Deck Occupants

PO-1. The needs of the flight crew as humans in a potentially hazardous work environment should be supported.

PO-2. The design should accommodate what is known about basic human physical characteristics.

PO-3. Peripheral activities which are indirectly related to the mission objectives should be supported.

PO-4. The design should account for major cultural norms.

Conflict Resolution

Those involved in the flight deck design process know that design decisions involve compromise. Economic, regulatory, safety, and operational constraints continually conflict. In the sense that human-centered design principles and guidelines are design constraints, they may conflict with other constraints, such as market, regulatory, physical, etc. More important, at least within the scope of this philosophy, is the fact that these principles and guidelines will sometimes create conflicts among themselves when design concepts and design decisions are being made.

We believe that a general priority order may exist for classes of principles. For example, those that involve the pilot as team member *may* generally be higher priority than those that involve the pilot as commander, which may generally be more important than those that involve the pilot as an individual operator and so forth. Fixed priorities may exist among individual principles as well. For example, principle PI-1 states that the pilot should be appropriately involved in all critical flight functions and tasks for which he or she is responsible. Yet in certain conditions, this involvement may exceed the attentional and information processing capacity of the pilot (a violation of PI-8, i.e., fundamental human limitations should not be exceeded). Hence, one might argue that PI-8 has a higher fixed priority than PI-1.

But in the final analysis, which principle or guideline takes precedence over another in regard to developing a specific design concept or making a specific design decision is usually context- and issue-specific. Therefore, methods and metrics are needed to identify and resolve conflicts among principles and guidelines. A multi-disciplinary team is recommended for resolving conflicts, rather than a single individual. Where major differences of opinion occur, trade studies might be appropriate to evaluate proposed design solutions based on different priority weightings of competing principles or guidelines. Test and evaluation will ultimately determine if the trade-offs that were made during the design process were appropriate. Part 2 of the full design philosophy document will address the issue of conflict resolution in greater detail.

REFERENCES

Billings, C. E. (1991). Human-centered aircraft automation: A concept and guidelines. NASA Technical Memorandum TM-103885. Moffett Field, CA: NASA Ames Research Center.

Dornheim, M. A. (1995). Dramatic incidents highlight mode problems in cockpits. In Aviation Week & Space Technology, January 30, 1995.

Jordan, N. (1963). Allocation of functions between man and machines in automated systems. Journal of Applied Psychology, 47(3), 55-59.

Palmer, M. T., Rogers, W. H., Press, H. N., Latorella, K. A., & Abbott, T. S. (1995). A crew-centered flight deck design philosophy for high-speed civil transport (HSCT) aircraft. NASA Technical Memorandum TM-109171. Hampton, VA: NASA Langley Research Center.

Sarter, N. B., & Woods, D. D. (1992). Pilot interaction with cockpit automation I: Operational experiences with the flight management system. International Journal of Aviation Psychology, 2(4), 303-321.

Wilson, W. W., & Fadden, D. M. (1991). Flight deck automation: Strategies for use now and in the future (SAE Technical Paper 911197). Presented at the 1991 SAE Aerospace Atlantic Conference, Dayton, OH.

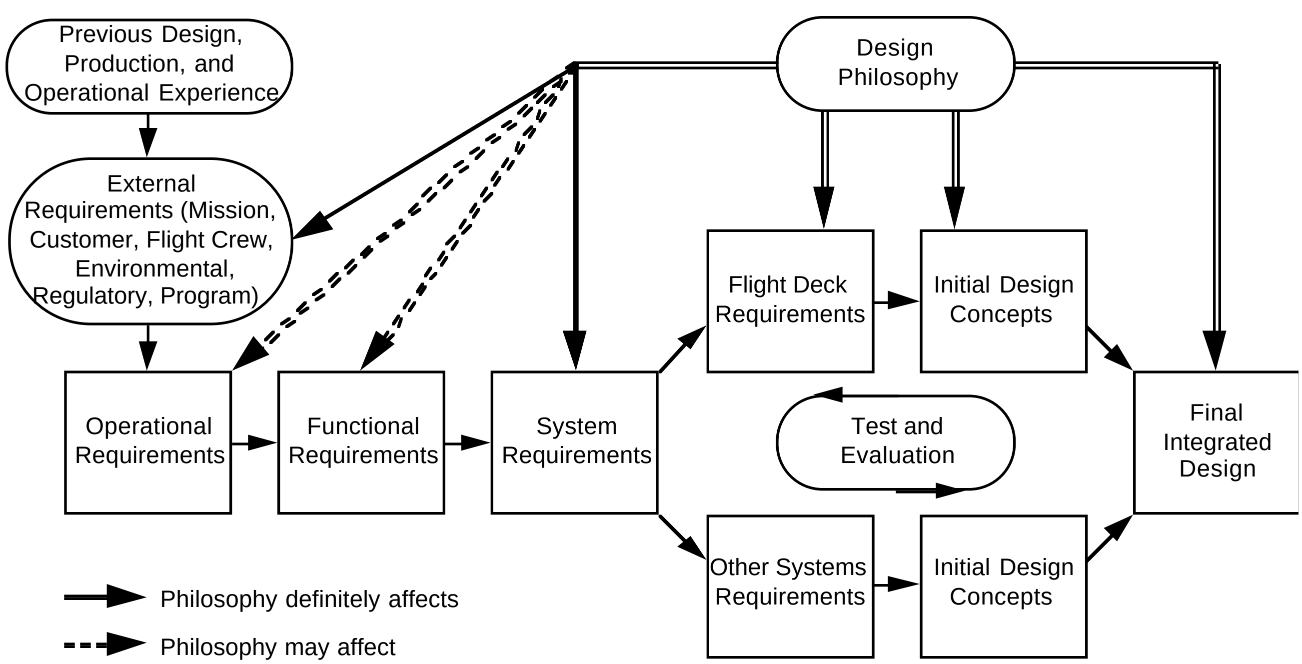

Figure 1. Simplified representation of the flight deck design process and the impact of the design philosophy.