

# Designing to Control Flight Crew Errors

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## ABSTRACT

It is widely accepted that human error is a major contributing factor in aircraft accidents. There has been a significant amount of research in why these errors occurred, and many reports state that the design of flight deck can actually dispose humans to err. This research has led to the call for changes in design according to human factors and human-centered principles. The National Aeronautics and Space Administration's (NASA) Langley Research Center has initiated an effort to design a human-centered flight deck from a clean slate (i.e., without constraints of existing designs.) The effort will be based on recent research in human-centered design philosophy and mission management categories. This design will match the human's model of the mission and function of the aircraft to reduce unnatural or non-intuitive interfaces. The product of this effort will be a flight deck design description, including training and procedures, and a cross reference or paper trail back to design hypotheses, and an evaluation of the design. The present paper will discuss the philosophy, process, and status of this design effort.

## HUMAN ERRORS AND GREAT EXPECTATIONS

"We all make mistakes." "To err is human." "Nobody's perfect." "You can't do everything." We tend to accept these age-old cliches as common sense truths. They are evidenced by our everyday existence. We all have flipped the wrong switch, deleted an important file, or ventured down a hallway only to forget why we were there. We have all made misjudgments or ignored data that was contrary to our current beliefs. These are examples of common human behavior—not abnormal or erroneous human behavior. In fact, it would be highly unusual if we did not act this way. However, in the aviation industry as well as many others, in designing human-machine interfaces, these behavioral tendencies are often not considered. Designers of systems often expect humans to act in unnatural ways, that is to say, not to be prone to these natural behaviors. Likewise, when accidents and incidents are investigated, investigators often judge humans according to super-human standards.

Imagine if we designed a computer system that was known to generate a lot of heat and we did not provide cooling. If the computer failed, would we state that it was computer error or design error? Would we blame the computer for generating too much heat? No. Since it was understood prior to design that the computer generated heat and had certain cooling requirements, we would classify the failure as a design error. However, in aviation

accident investigations, the causal factor for the accident is attributed often to air or flight crew (pilots, copilots, etc.) error rather than being attributed to the designs which do not always account for human behaviors.

The point here is that we assign blame to humans for being human, for acting naturally. It is as if we had super-human expectations. Is it the human's fault to forget a name that she just heard in a crowded party where she was introduced to 20 new people in five minutes? Is it a human error for a person to forget the phone number of the house he lived at fifteen years ago? Is it a human error for a person to get lost if his map is incorrect? Is it a human error for an infrequent traveler to ask where the "bathroom" is when the natives only know it as the "toilet"? In aviation flight operations, incidents and accidents resulting from similar events are routinely classified as being the flight crew's fault.

While there is much to learn about human behavior, we do have a large body of information regarding it. Although there are significant individual differences between humans, there are also many similarities. We know in order to perform properly, humans need to be aware of their surroundings; need to be alert and attentive; need to have authority with responsibility; need to understand what their role in the mission is; and can only deal with a small number of variables. We should design systems to satisfy these and other human requirements. However, many human-machine designs do not fulfill these requirements; Aircraft flight decks (both classic and modern) are teeming with examples of such designs.

## THE AIRCRAFT FLIGHT DECK CONTEXT

### Current flight deck designs - Can vs. Should

Current flight deck designs often take human physical behavior into account but rarely appear to take human cognitive behavior into account. For example, they will address factors such as visibility and legibility, and workload (e.g., the pilot can't do more than 'X' things at once), but they often will not address the issue of whether the information or interface is intuitive. They do not always consider pilot performance over time. They usually ask the question "Can a human operate this?" instead of "Is this the way the human should operate this?" As a result, we see a number of accidents and incidents which are caused, not by human error, but by the mismatch between human and system behavior. [1]

Modern flight decks ( as a result of design, the design philosophy, training and procedures) generally present a

mismatch between human behavior and operational environments. The quiet, dark cockpit philosophy (originally designed to reduce nuisance lights and alerts) has been combined with significant programmed or scheduled automation to create an environment which may lull the human into a state of inattentiveness. In modern flight decks, pilots do not always have authority over flight critical functions (e.g., electronically controlled engines that shut down automatically when they detect a failure) or that authority might be difficult to wield (e.g., a combination of autopilot and flight modes that do not allow the pilot to disengage the automation in “normal” ways.) Many flight decks are automated to the point that pilots are often reluctant to disagree with or override the automation, even when it is the pilot’s role to manage and evaluate the automation. In this case, the pilot essentially becomes part of the automation or subservient to it. Finally, pilots of modern flight decks are often overwhelmed with a large number of modes, display types, display formats, alert types and messages. And, these are just some of the more obvious problems with current flight deck designs.

### **Challenges to design**

Although it is easy to throw stones at current flight deck designs, it is a more difficult task to correct those problems. There are a number of impediments to modifying designs to address these problems [2]. One of the biggest ones is that despite their drawbacks, the modern flight decks do function well (contributing to the overall low aircraft accident rate) and so many people are reluctant to change anything. However, there are those who believe that the only way to improve the current safety record in a significant way requires wholesale changes in the flight deck design, training, and procedures. A recent report by the Federal Aviation Administration (FAA) [3] presents a number of changes that would be required to address these issues. Several of those changes sum to the conclusion that evolutionary, piece-meal design changes will not generally lead to significant improvements in safety. The following represent points from the document: Flight deck designs cannot be “human factored” near the end of the design; There is not a simple, single-point solution to every human factors problem; Many problems must be addressed in and at the total flight deck design level.

### **HUMAN-CENTERED FLIGHT DECK DESIGN**

While humans are trainable, they are not nearly as malleable as is technology. Current flight deck design has been described as technology centered design—meaning that the technology was the primary consideration of the design and humans were after thoughts. Humans have dealt with this technology domination by relying on their unique traits of flexibility and adaptability. But, these traits have been pushed to the limit. Because advanced aircraft are, and will continue to be, so heavily automated due to demands for efficiency and safety, principles of human-centered design (giving more emphasis on human behavior) should be followed when designing these new aircraft, particularly

their flight decks. Billings [4] lists and gives examples of these principles for human-centered automation.

The basic tenet of these principles is the following, “The Human Operator Must Be in Command.” In an aircraft, the pilot is to remain always in command, even when he or she is using automation. Thus, automation, including air traffic management automation, must never remove the pilots from that command role. For example, pilots must be able to override the authority of flight control automation, even within normal operating limits. However, override authority by itself does in no way equate to command. Command entails both authority and awareness. Billings 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 pilot induced mode changes will provide better awareness. Thus human-centered design starts at the overall function 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 was developed at NASA Langley Research Center[5]. 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 iteratively within the design process. The philosophy assumes that the flight crew will remain an integral component of the flight deck for the foreseeable future because human skills, knowledge, and flexibility are required in the safe and efficient operation of complex systems in an unpredictable and dynamic environment. The philosophy recognizes that humans and machines are complementary and that safety and efficiency of flight will be maximized when this complementary nature is supported by the design. The philosophy seeks to elevate design issues associated with the understanding of human performance and cooperative performance of humans with automation to the same level of importance as the past focus on purely 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 one 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 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. These roles are: Pilots as team members; pilots as commanders; pilots as individual operators; and, pilots as flight deck occupants. A

framework for detailed guidelines was presented which accounts for both the pilot roles and the different categories of flight deck features (i.e., displays, controls, automation, and alerts)."

### **Function Allocation and Involvement**

Function allocation is an important element of flight deck design. It is at the heart of human-centered design. The following function allocation guideline was distilled from Billings [4] and Palmer et al. [5]: 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 situation awareness. When engagement is low due to factors such as boredom, complacency, or fatigue, the pilot enters a state described by Pope and Bogart [6] as a hazardous state of awareness. They developed a procedure to identify hazardous states of awareness based on electroencephalogram (EEG) signals and other physiological indices of awareness. Their model for predicting whether the flight crew will experience inappropriate or hazardous states of awareness involves three sets of factors: predisposing, inducing, and counteracting. Examples of predisposing factors are how likely the individual is to become complacent, bored, or absorbed. Inducing factors examples are sensory restriction, such as monotony, and stressor preoccupation from life situations. The hypothesized counteracting factors would negate or prevent the effects of the predisposing and inducing factors for hazardous states. Examples of such factors are attentional competence, communication flow, and task engagement. Pope et. al. [7] have developed a system which measures mental task engagement. Because human/automation task allocation strongly influences task engagement, this engagement index can be used to evaluate various function allocation schemes.

### **Flight Deck Mission Categories**

Abbott and Rogers [8] proposed combining human-centered design principles with a systems-oriented approach to designing new flight decks which will meet overall mission requirements. With this approach, they suggested that system integration problems would be reduced. This approach requires that mission requirements are defined before any designing of the flight deck or other aircraft systems occur. In their study, a mission goal was assumed for an aircraft to be that of moving "passengers and cargo from airport gate to airport gate safely and efficiently." Then, the overall function of the flight deck systems was assumed to be that of managing the mission of the aircraft. Both normal and abnormal situations were considered for the accomplishment of the mission. Four levels of mission management were 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 Billings [4] indicates that the behavior and purpose of the automation should be clear to the user. Thus, information relevant to the real task, 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**

Abbott [9] developed a display design process based upon function allocation that decomposed "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 content information may or may not be raw data, and can be synthesized from underlying data. Also, the information was presented in such a form as to be more appropriate for the task. Abbott demonstrated this task-oriented design process for an aircraft engine display. Using this process, pilots, in a simulator, had better performance with the resulting display over traditional displays, as well as increased pilot preference for the new display. This particular display was used by the pilot to control engine thrust and monitor the engine health. Rather than provide individual pieces of information which the pilot had to combine (a task ill suited for humans and not directly related to the task), the display presented the information after it was combined. This meant that information traditionally provided on multiple displays was integrated or synthesized into one display, thus reducing the pilot's effort to do the task by only having to refer to one versus multiple displays. This synthesized quantitative information was presented in a form that was processed qualitatively by the pilots; a level of processing sufficient for the task. The key to successfully using this function allocation process is understanding the real task the user or flight crew must perform.

### **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" [4],[10]. To control the effect of brittleness, most systems require a person to be incorporated in the system. This places the human in the unique role of troubleshooter and the best and last defense. This approach has been identified as having human performance problems, especially in the cockpit. Parasuraman [11] points out that our responding 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 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 design of the flight deck and the supporting training and procedures do not readily address this human function. Flight crews are only provided training for normal operation and anticipated failures. If a failure is novel (unanticipated), the flight crew may not respond properly, as supported by the number of inappropriate crew responses to failures [12]; however, responding to novel failures is an accepted part of the flight crew's job.

Rogers et al. [13] presented a framework for real-time fault management which 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 system design.

### **ERROR PROOF FLIGHT DECK PROGRAM**

NASA Langley Research Center has implemented a research program that seeks to develop a human centered flight deck design driven by requirements from the top downward, and to demonstrate the effectiveness of such a design in reducing crew errors while also reducing training costs. This program, although recognizing and capitalizing on the successes of the past, will not be constrained to designs simply because "that is the way it has always been done." In this sense, we are operating with a clean slate. The program is called, "Error Proof Flight Deck." The title emerged from the fact that human 'error' is inevitable, being part of our behaviors, and therefore, the goal is to prevent the flight deck from allowing the negative consequences of these 'errors' to propagate to the mission. That is, the "error proof" is from a mission perspective, not the traditional human error viewpoint. This program will continue for five years and is described below.

The goal of this research program is to develop a top-down human-centered design of a flight deck. While it is impossible to design any system entirely 'top down' (see [2]), it is desirable to take a more integrated, and deliberate design approach that continually relies on the top mission requirements, guidelines, and principles as its basis.

#### **Design Attributes**

Some of the attributes of such an error proof flight deck design are the following: To provide better pilot awareness by reflecting his or her mental models in design and providing information at the level of usage (e.g., flight-communication-systems-task management, tactical-strategic); to improve pilot engagement by increasing his or her involvement with the task (in appropriate ways) without increasing workload; to provide involved control over all critical flight parameters (not just override capability); to clearly define

the roles, functions, and responsibilities of the pilot-flying and pilot-not-flying in terms of the mission (instead of in terms of the equipment); to reduce the number of flight guidance modes; to appropriately integrate information; to insure format, context, and procedure consistency; and to integrate training with the flight deck design.

#### **Target Assumptions**

Prior to beginning the design, certain assumptions about the aircraft and its mission must be made. The mission chosen for this design is that of a corporate business jet. This aircraft was selected because it has some commonalities with both the commercial transport domain and the general aviation domain, and therefore would have results applicable to either.

**The Aircraft:** The target aircraft normally has 2-crew operations but is certified for single pilot operation. It weighs more than 12,500 pounds and is subject to FAA Part 25 regulations. It is certified to operate as a business jet (Part 91), an air taxi (Part 135), and a scheduled service airline (Part 121). It is capable of carrying 20 to 30 passengers. It has a range of 3000 miles (coast to coast with instrument flight rules reserves), a top speed of 0.9 Mach, and is powered by two turbo-fan engines. The aircraft is equipped with Automatic Dependence Surveillance B and a Global Positioning System/Local Area Augmentation System. The aircraft is equipped with a high bandwidth data link and a high quality voice ground communication system.

**The Mission:** This target aircraft is owned by a company so that the pilots are employees. The aircraft is part of a fleet, and the pilots are part of the company's crew. The pilots all have commercial ratings. The company is an international company so it must comply with Federal Aviation Regulations and the European Joint Aviation Regulations. Also, the flight crew is multi-national and the flight deck must accommodate multi-cultural pilots. The aircraft is capable of landing in Category II conditions. The flight duration ranges from 45 minutes to 5 hours with the typical flight lasting 2 to 2.5 hours.

#### **Approach**

The Error Proof Flight Deck research team at NASA Langley is comprised of engineers, computer scientists, pilots, and psychologists. The team has extensive experience in the aviation domain having been involved in numerous flight deck designs and projects. A major advantage for an agency such as NASA to take on this research project is that it can afford higher risk. Note, that this does not relieve the team from the responsibility of addressing practical operational needs such as certifiability, operational costs, and training; rather it frees the team to explore high payoff/high risk solutions.

The general approach being taken in this effort is one of iterative top-down design. Each iteration provides more depth and breadth both in the definition of the concept and the evaluation of the concept. During each iteration,

representatives from industry, the airlines, and the pilot community will be consulted to provide input for both the design and the evaluation. As the design matures, industry will have a greater involvement to insure that practical details have not been overlooked and to increase technology transfer. The final detailed prototype will be developed primarily by industry.

**Iterative Mission Decomposition:** The design begins with the mission decomposition described above (flight management, communications management, systems management, and task management) and continues with the break down of that decomposition. Each subcategory will be defined in terms of the design philosophy and function allocation principles defined above. This includes defining the roles of the flight crew and the information and task requirements. Prior to defining the next level down, a prototype of the flight deck *at a corresponding level of granularity* will be developed.

**Iterative Prototyping:** Once the flight crew roles, information, and task requirements have been defined, the design team will develop a prototype of the flight deck. Each design decision made for the flight deck will have a corresponding rationale that is traceable to the design guidelines, rather than to previous designs. The prototype could take the form of a narrative description, a collection of pictures, software (workstation) prototypes, concepts implemented in simulations, or even actual flight decks. The depth of the implementation of the prototype depends on the depth of the mission decomposition. If the mission decomposition is at a high level (less detailed), then the prototype will be at a high level (i.e., storyboard or canned computer displays). The deeper the decomposition, the more detailed the prototype. The rationale for this is both economy and effectiveness. When the mission decomposition is still at a high level, it would be premature and expensive to try to implement the concept in a simulation facility. Likewise, it would be inappropriate to carry the mission decomposition too far before realizing it in a prototype. The danger in doing so rises from the fact that as one performs the decomposition, it is extremely tempting (and, indeed, necessary) to make assumptions about the implementation. Formerly, these assumptions were often made in isolation, without regard for other systems or functions. This led to inconsistencies and conflicts which led to confusion which led to errors. However, this program's iterative approach to prototyping will allow general principles to be established early, and when details necessitate a violation of those principles, they will be explicitly and uniformly addressed.

**Iterative Evaluation:** The level of evaluation will depend largely on the depth of the prototype. In the initial phases of the program, the evaluation will likely be reviews by experts in the aviation and manufacturing fields as well as those in the human factors areas. Later in the workstation and early simulation phases, evaluation will likely require a series of operational pilots to act as

test subjects. It is important to get a large and diverse pool of test subjects so that the concept will not be tailored to a specific class. In the final phases of testing, it will likely be necessary to bring in pilots to participate in long duration studies where they will be exposed to in-depth training and a more realistic operational environment.

**Scenario Development.** An important aspect of evaluating any concept is the flight mission scenario suite that is used for evaluations. If it is too narrow or unrealistic, it will likely lead to inaccurate results. Scenarios are important because they ground the prototype to the real world (even if the prototype is not very detailed). The scenarios used in evaluation must be diverse and cover the extremes of the envelope. They should include system and functional failures, adverse environments, cultural differences, and stereotypical human behavior as well as normal operations.

**Metrics and Measures.** "Improved safety, reduced accidents, and reduced errors" are often touted noble goals but are difficult to prove until many years after implementation. Responses to accidents and incidents that occur in the real world are difficult to realistically duplicate under controlled conditions largely because the experimental subjects are primed to respond in some way. Generally, errors are induced by increasing workload on these subjects. However, this increased workload may not be representative of real world failures. One way of addressing this problem is to develop error metrics that are based on error precursors rather than on the actual errors. Error precursors are events or states which are necessary for errors to occur, however they are not sufficient. The ratio of precursor events to error events may be very large, meaning that precursors are more likely than errors. Thus if the number of precursor events can be reduced, the number of error events should also be reduced.

### **Product**

Perhaps the most important product from this research will not be the actual flight deck prototype, but rather the guidelines, methodologies, and learning that goes into creating a successful prototype. Designers may or may not choose to implement the actual design for a number of different reasons ranging from the appropriateness of the design to their problem, to their need to have a flight deck that is different from the competition. However, the guidelines, methodologies, and lessons learned should still be applicable to their design and some specific aspects of the design may also directly transfer to their design. (Note that the danger here is in taking pieces out of the design and incorporating them into old designs without addressing the overall impact of mixing the old with the new. This is not to say that it cannot be done, but that it must be done cautiously.)

### **SUMMARY**

For many years, the human factors community has pointed out the many flaws in the human/machine integration in aircraft. Calls for changes in design are

frequent, yet responses are few. This is largely due to the expense and risk of fundamental design changes. We believe that new design guidelines, methodologies, and prototypes are called for and that it is NASA's role to establish this process. This research program is being implemented to meet this challenge and to take the risk. As mentioned above, it may not be appropriate for all aircraft designs. However, such a design could serve as a goal for the technological evolution of future flight decks. But first, the Error Proof Flight Deck concepts must be implemented, if only to create a test case or prototype, to assess its impact on safety and efficiency.

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