WINGS: A NEW PARADIGM IN HUMAN-CENTERED DESIGN

Paul C. Schutte
NASA Langley Research Center
Hampton, Virginia

INTRODUCTION

Many aircraft accidents/incidents investigations cite crew error as a causal factor (Boeing Commercial Airplane Group 1996). Human factors experts suggest that crew error has many underlying causes and should be the start of an accident investigation and not the end. One of those causes, the flight deck design, is correctable. If a flight deck design does not accommodate the human's unique abilities and deficits, crew error may simply be the manifestation of this mismatch. Pilots repeatedly report that they are 'behind the aircraft', *i.e.*, they do not know what the automated aircraft is doing or how the aircraft is doing it until after the fact (Wiener 1989, Rudisill 1994). Billings (1991) promotes the concept of 'human-centered automation;' calling on designers to allocate appropriate control and information to the human. However, there is much ambiguity regarding what it means to be human-centered. What often are labeled as 'human-centered designs' are actually designs where a human factors expert has been involved in the design process or designs where tests have shown that humans can operate them. While such designs may be excellent, they do not represent designs that are systematically produced according to some set of prescribed methods and procedures.

This paper describes a design concept, called *Wings*, that offers a clearer definition for human-centered design. This new design concept is radically different from current design processes in that the design begins with the human and uses the human body as a metaphor for designing the aircraft. This is not because the human is the most important part of the aircraft (certainly the aircraft would be useless without lift and thrust), but because he is the least understood, the least programmable, and one of the more critical elements. The *Wings* design concept has three properties: a reversal in the design process, from aerodynamics-, structures-, and propulsion-centered to truly human-centered; a design metaphor that guides function allocation and control and display design; and a deliberate distinction between two fundamental functions of design, to *complement* and to *interpret* human performance. The *complementary* function extends the human's capabilities beyond his or her current limitations—this includes sensing, computation, memory, physical force, and human decision making styles and skills. The *interpretive* (or hermeneutic, Hollnagel 1991) function translates information, functionality, and commands between the human and the aircraft. The *Wings* design concept allows the human to remain aware of the aircraft through natural interpretation. It also affords great improvements in system performance by maximizing the human's natural abilities and complementing the human's skills in a natural way. This paper will discuss the *Wings* design concept by describing the reversal in the traditional design process, the function allocation strategy of *Wings*, and the functions of complementing and interpreting the human.

THE DESIGN PROCESS: HUMAN-CENTERED AIRCRAFT DESIGN

The traditional approach to aircraft design (Figure 1) is to first define the mission requirements (Palmer, *et. al.* 1995). These requirements are used to develop the aircraft operational requirements, which are then used to develop the aircraft functional requirements. The operational and functional requirements give rise to the aircraft system requirements. Once the requirements for the aircraft systems are defined, the flight deck requirements are developed. Generally, the flight deck is not considered until the end of the design process. Human factors experts are often brought in to 'human factor' the flight deck design, as if there was a well established procedure for doing so, similar to 'ruggedizing hardware' or 'sound proofing the cabin'. Any problems that cannot be 'human factored' in design can be addressed with aggressive training of the flight crew.

The fallacy in this approach is considering human factors to be a methodology or science similar to ruggedizing (*e.g.*, structural mechanics and dynamics) or sound proofing (e.g, acoustics). It is not similar. First, human factors is not a discipline that retrofits well. In the case of aircraft, when the system functions and the flight control modes have already been defined, major design decisions that affect the human-centeredness have already been made. In other words, there may be features in the design that dispose humans to error and no amount of display change or training will nullify that disposition. The second difference between areas such as acoustics and human factors is that there is no *established* set of human factors tools and principles that will generate a repeatable and consistent design. There are some conventions for things such as color, reach, legibility, etc., and a few for cognitive aspects, such as involvement, awareness, and human/automation interaction, but there is still considerable debate in the human factors community over standards and procedures. This lack of maturity is not due to the age of the field, but rather the difficulty of the subject matter, namely understanding humans. Human beings are incredibly complex, apparently non-deterministic entities. Designing systems to interact with humans is extremely difficult.

What often saves potentially bad designs is the fact that humans are indeed adaptable, flexible, and diligent. While a large number of accidents are attributed to human error, there are no data on the number of accidents averted through human intervention. While it is true that 'To err is human', it is also true that 'Humanity covers a multitude of design sins'. In fact, one of the primary reasons for including humans in the system is to take advantage of their adaptability and creativity. Humans make the system work, and at this point in the maturity of technology, humans are essential.

At this point in the discussion an interesting irony emerges. On one hand, the flight crew appears to be a critical link in the chain of both averting and causing accidents. On the other hand, the design of the flight deck is left to the end of the design process where there is little flexibility remaining to accommodate the human.

There are a number of valid arguments for the traditional approach: (1) Humans are flexible and creative so they can handle less-than-optimal designs. (2) The current approach has produced certified designs and a change would involve more risk. (3) Designing for the human is too ill-defined a process (*e.g.*, there are no Navier-Stokes equations for human beings)—designers should perform the defined, procedural design tasks first. (4) The systems must be defined before the system controls in the flight deck can be defined (*i.e.*, put the horse before the cart). However, there are compelling counterpoints to these arguments: (1) While humans are flexible, the complexity of the flight mission, not the flight deck design, should exploit that flexibility. (2) Because the human is so critical in the aversion and cause of accidents, the most fertile ground for accident reduction may be found in addressing the human element of the aircraft more directly. While the risk of such an approach may be great, the risk of allowing the accident rate to continue as it is may be greater. (3) Sometimes it is better to tackle the more ill defined problems first so that they can receive more effort, and postpone working on the 'easier' problems. (4) The order of design may be more like a chicken and egg issue rather than a horse and cart issue (*i.e.*, one set of design constraints does not necessarily beget the other).

The approach advocated in this paper (Figure 2) is to begin the aircraft design with the mission requirements, but from the mission requirements define the roles and responsibilities for the flight crew. Then a flight deck functional concept can be developed. From this concept, system and airframe design can proceed. The more difficult task of designing for humans is faced at the beginning of the design process, and the more tractable and procedural processes of designing for aerodynamics, materials, and propulsion are left to the end. In this design, the flight deck conforms to the human, and the aircraft conforms to the flight deck. What does it mean for the flight deck and aircraft to conform to the human? A simple description is having an aircraft that is natural to use. Therefore, the *Wings* design concept looks to nature to provide the blueprint for design, namely the body metaphor.

FUNCTION ALLOCATION: THE BODY METAPHOR

In the design of modern aircraft it is critical to address the allocation of functions to humans and automation. There are a number of taxonomies and categories for describing function allocation in design (Palmer, *et. al.* 1995, Billings 1991, Riley 1989, Rogers 1996). Most of these studies characterize different levels of allocation between human and machine, ranging from total allocation to the human to total allocation to machine. In most design decisions, these extremes are not used. Rather, there is a shared allocation of responsibilities between human and machine for all functions (Rogers, 1996). Further, different functions require different function allocation strategies and the allocation for one function may influence the required allocation for another. For example, how a particular function (*e.g.*, hydraulics system management) is allocated between the human and the machine can have consequences for the allocation of another function (*e.g.*, gear and high lift device control). This interdependence of allocation strategies can make the holistic design of an aircraft a difficult task. The key is to have a predetermined allocation strategy before the allocation process. The *Wings* concept looks to nature to provide such a strategy. The strategy is to base allocation decisions on the natural allocation of functions between the mind and the body. The mind/body and human/aircraft relationships are virtually analogous. The mind cannot move by itself, the human cannot fly. The mind cannot sense the outside world, rather it relies on sensors (*e.g.*, eyes, ears, skin) to sense information from the outside world and from the body itself. Likewise, the human in an aircraft often must depend on sensors to provide information regarding the outside world. The mind controls much of the body's functions, but often only in coarse ways. These coarse commands are interpreted into fine motor performance using reflexive muscle responses in the body (*e.g.*, the reflexive bending of the ankle while walking). Likewise, the aircraft often has distributed mechanisms that interpret general commands and perform mechanical responses (*e.g.*, yaw dampers). In the *Wings* design concept, the appropriate level of automation for an aircraft function is determined by the level allocated to its' analog in the human body. Systems like fuel pumps and fuel filters would function autonomously like their analogs, the heart and liver. All higher level functions would be initiated by the human, just as the mind initiates all gross motor actions. The human would be at the 'head' of the aircraft, and therefore should have fewer surprises.

The *Wings* design concept uses a mind-centered, body -metaphor approach to automation, keeping the mind at the center of and as the initiator of all major activities of the system. The automation serves to augment and enhance the user in performing those activities. A major advantage of this allocation strategy is that design can focus on overcoming human error problems that are truly human, such as wandering attention and poor understanding of the mission, rather than problems that have arisen from unnatural function allocation. In other words, there are problems and errors intrinsic to human nature that would occur in any domain and there are problems that result from human interaction with a design or interface. These two classes of problems may require different remedies and solution approaches. By making the aircraft design similar to that of the human body, the second class of problems may be subsumed by the first and require only one type of remedy. Another advantage of the mind-centered, body -metaphor approach is that the human mind already has several efficient preprogrammed routines for dealing with and operating the body. These natural routines could be exploited to deal with the vehicle so that additional routines would not have to be developed. Finally, the body metaphor for design offers less risk than other untried design methodologies in that it has been proven by the process of evolution.

How does this design strategy compare with that of modern flight decks? Characters from two movies, RoboCop™ and Star Wars™, exemplify the two design concepts. In RoboCop™, the title character is a human mind augmented by an integrated human-machine. All major actions of the system are controlled by the human mind. There is significant augmentation to the normal human skills (both physical and mental). Intent, style, and ingenuity originate from the mind while strength, precision, skill, and sensing are enhanced by the automation at the mind's command. RoboCop™ could be considered to be a product of the *Wings* design concept. On the other hand, R2D2 of Star Wars™ represents the product of a more traditional design strategy—an intelligent associate. Although a human commands R2D2, the execution of these commands is based on R2D2's programmer's interpretation. Because these commands are often carried out at a later time or place, the human may not be able to monitor the associate. Consequently, the associate may do what the human commanded, but not what he intended. In modern flight decks, the flight management/autoflight system acts as an intelligent associate. It is given a series of commands by the human and it then goes off and acts on those commands. It is true, that the human can take over any task at any time, but what happens when the human is inattentive or unaware of all the details of how the automation is programmed? We often see errors occur, especially if the automation is programmed using a logic that is different from the human's logic.

COMPLEMENTARY AND INTERPRETATIVE DESIGN

The human body relates to the mind in two ways. The body complements the mind and interprets for the mind. The body complements the mind by allowing it to do things that it alone cannot do. The mind cannot move, manipulate objects, or survive on its own. The body provides functions allowing the mind to do these things. It provides a life support system and a protection system for the mind. Also, the body interprets various signals or stimuli from the outside world into a form that the mind is equipped to deal with. The body translates sound, light, touch, pressure, and chemical content into electrical signals used by the mind. The body also collects information regarding the status of itself and communicates that to the mind. The body interprets its' status to the mind when something is damaged (pain), is not functioning properly (numbness), or is operating correctly (muscle sense). Finally, the body executes commands from the mind by interpreting those signals into muscle movements. The concept of complementing and interpreting is not new to aircraft and flight deck design. Indeed, people would not be able to fly if it were not for these two functions in modern aircraft. The difference between the *Wings* design concept and others is that it seeks to design a complementary and interpretive flight deck that is mind-centered using a function allocation strategy that is based on the body metaphor.

It is important to note that the body metaphor is meant to be a template for function allocation, but not a limitation on design. This is especially true when considering the complementary aspects of design. The design of the human body does not allow the human to see behind him without moving the body around. However, the aircraft design might allow for vision in 360 degrees around the x, y, and z axes. This design decision is consistent with the *Wings* design concept (*e.g.*, eyes in the back of your head). Likewise, the aircraft design can be used to complement human deficiencies in areas such as memory, attention, and even reasoning strategies. But the metaphor should be kept in mind as new functions are implemented. Thus the designer wanting to add a new complementary functionality that humans do not have, should imagine what it would be like if humans had evolved with such capabilities. Humans do not have wings, but what would it be like if they did?

Complementary Design

The aircraft design should complement the human by assisting in the avoidance of human errors and in performing the mission. The former can include sensing mechanisms, memory aids, and computational tools. An exciting area for complementing the human is reasoning strategies, *e.g.*, helping the crew know when to shift from their natural reasoning strategy, say goal-driven, to another strategy, say data-driven. It important to note, that the body metaphor does not eliminate human error, it eliminates human/machine interaction error. Complementary design must be used to address true human error.

Complementing the human for the mission, would include providing all the information and capabilities necessary to perform the mission safely and efficiently. The *Wings* concept prescribes complementing as if humans were born to fly—as we are now born to walk. This requires distributing control mechanisms for flying throughout the aircraft, just as many of the control mechanisms for walking (*e.g.*, balance, muscle movements, muscle coordination) are distributed throughout our bodies.

Interpretive Design

The aircraft should interpret the human commands to the aircraft and interpret phenomena from the outside world to the human in a meaningful and manageable fashion. The direct control of individual systems should be deliberate and at a coarse or high level (*i.e.*, more 'what' than 'how'). Humans naturally know how to lift their hands and never confuse them with their feet. The human does not need to consciously think about the fine details of how arm movement commands are carried out. The details are not as important as the explicitness of the command. Such designs are called *hermeneutic* by Hollnagel (1991) and *transparent* by Winograd (1987). The level of detail in both the information and control provided by the aircraft should be directly dependent on the task (Abbott 1989). In interpreting information from the outside world, the design should use the body metaphor as well. For example, tactile information such as vibration might be presented in a tactile manner, say vibrating a control (similar to what a stickshaker does today) or even the pilot's seat.

Often the human is overloaded on a particular interface channel and cannot receive or present information using it. This does not mean that the information cannot be presented, but rather that its content should be presented in the most natural way on another channel. As an example, consider modern methods of communicating with the deaf. The most common form of communication is American Sign Language (ASL). ASL is actually a different language from say, English or German. If the deaf person could hear at one time, he will have to learn the new language and translate it into his first language. An alternative to ASL is Cued Speech (Fleetwood & Metzger 1997). In Cued Speech, the 'speaker' simply represents phonemes (*i.e.*, sounds) using hand and mouth gestures. Thus the cuer can communicate in English, German, or Spanish. The 'hearer' does not have to learn a new language, just a new way of hearing. This is an example of presenting the same information over a different channel. It may be that this technique could make use of underloaded channels to send and receive information that cannot be transmitted over the channel of choice either because it is already loaded or is not amenable to presenting the information. An example of this in flight deck design might be to transmit the feeling of 'numbness' visually or aurally to let the pilot know that a certain sensor or suite of sensors has failed. Of course, one must be careful not to overload the human with too much information. Obviously much basic research is required to explore these possibilities. However, the possibilities are intriguing.

When Complementary and Interpretive Conflict

There are times in the design process where tradeoffs must be made between complementing and interpreting. For example, it may be more appropriate to use nonintuitive logic because it is more efficient. Or, it may be that the complementary aspect of the design simply has no analog in the human mental repertoire. In the first case—deliberate departure from the way humans naturally think about things—the designer must take great care to provide extraordinary measures to assist the flight crew in dealing with an unnatural system. This help can come in the form of on-line explanation, memory aids, and ultra-obvious interfaces (Norman's affordances 1989). Training is also an important part of assisting the human. However, in this case, training requires the user to learn and remember something that is unnatural, thereby increasing the opportunity for error. Flight crew performance of an unnatural task is better handled in design. Training is more appropriate for the second case, where the human is being taught something that is new to his nature but not necessarily contrary to it. The more important of these areas are the fundamentals and physics of flight. Since humans do not naturally fly, they must be taught these principles. There are many that argue that piloting an aircraft should be as easy as driving a car. However, by the time most people are ready to drive a car, they have had ten to fifteen years of experience in negotiating in a 'two dimensional' environment. A three-year old instinctively knows to lean into a turn as she runs. Driving a car is just a small extrapolation from our walking experience. But three-dimensional, aerodynamic negotiation is not in our nature. Some of its properties can be discovered in activities like underwater swimming, but even here the nature of buoyancy prevents us from having an accurate model. So, even for an aircraft designed using the *Wings* concept, humans must learn how to fly. The design process allows the pilot to avoid having to learn things that have nothing to do with flight or the mission.

CONCLUSIONS

If humans were meant to fly, we would have more than just wings. We would have an internal navigation system, we would have legs capable of landings, takeoffs, and aerodynamic concealment, and we would have the knowledge of flight instinctively. We have found that we can overcome these deficiencies. We have done so by brute force based on the advances of technology. The *Wings* design concept is revolutionary in the original sense of the word. It is completing the circuit to the way nature might have meant for us to fly.

It should be noted that the author is not recommending this approach for every aircraft design. Economics may prevent an aircraft of this type from being built in the present day because it may require an airframe and systems design which are too expensive to build. However, such a design could serve as a goal for the technological evolution of flight deck and aircraft design. But first, it must be implemented, if only as a test case, to see if it has value in the areas of safety and efficiency.

REFERENCES

Abbott, T. S. (1989). *Task oriented display design: concept and example* (NASA TM-101685). Hampton, VA: NASA Langley Research Center.

Billings, C. E. (1991). *Human-Centered Aircraft Automation Philosophy: A Concept and Guidelines.* NASA TM-103885. Moffett Field, CA: NASA-Ames Research Center.

Boeing Commercial Airplane Group. (1996) *Statistical Summary of Commercial Jet Aircraft Accidents, World Wide Operations, 1959-1995.*
Fleetwood, E. and Metzger, M. (1997) *An Analysis of Cued Language Based on Linguistic Principles.* In Press.
Hollnagel, E. (1991). The phenotype of erroneous actions: Implications for HCI design. In G. R. S. Weir & J. L. Alty (Ed.), Human-computer interaction and complex systems (pp. 73-118). New York: Academic Press.
Norman, D. A. (1989) *The Design of Everyday Things,* New York: DoubleDay.
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 TM 109171. Hampton, VA: NASA Langley Research Center.
Riley, V. (1989). A general model of mixed-initiative human-machine systems. Proceedings of the Human Factors Society 33rd Annual Meeting, Vol. 1, 124-128. Santa Monica, CA: Human Factors Society.
Rogers, W. H. (1996) *A Principled Approach to Allocation of Flight Deck Functions.* Personal Coorespondence.
Rudisill, Marianne, (1994) *Flight Crew Experience with Automation Technologies on Commercial Transport Flight Decks* in Human Performance in Automated Systems: Current Research & Trends.
Wiener, E. L. (1989). *Human Factors of Advanced Technology, "Glass Flightdeck" Transport Aircraft.* NASA Contract Report No. 117528. Moffett Field, CA: NASA Ames Research Center.
Winograd, T and Flores, F. (1987) *Understanding Computers and Cognition: A new foundation for design.* Addison-Wesley

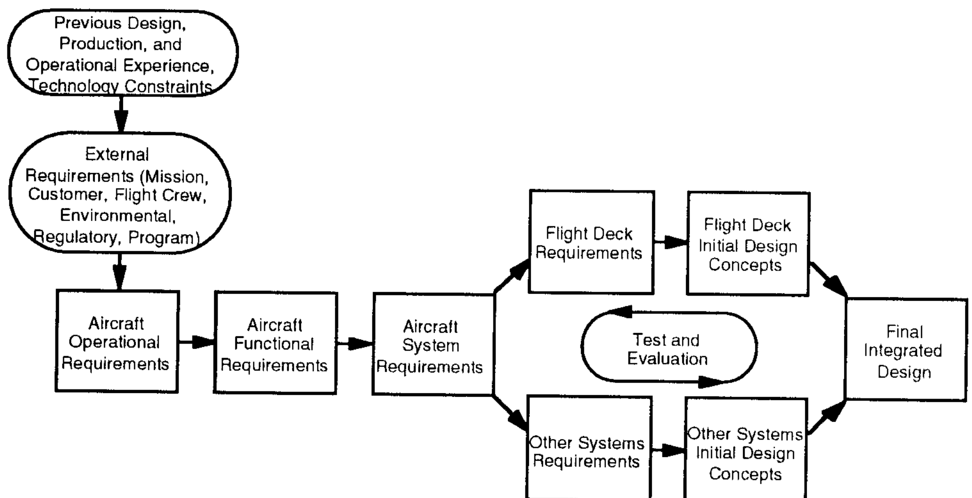

Figure 1. Simplified representation of the flight deck design process.

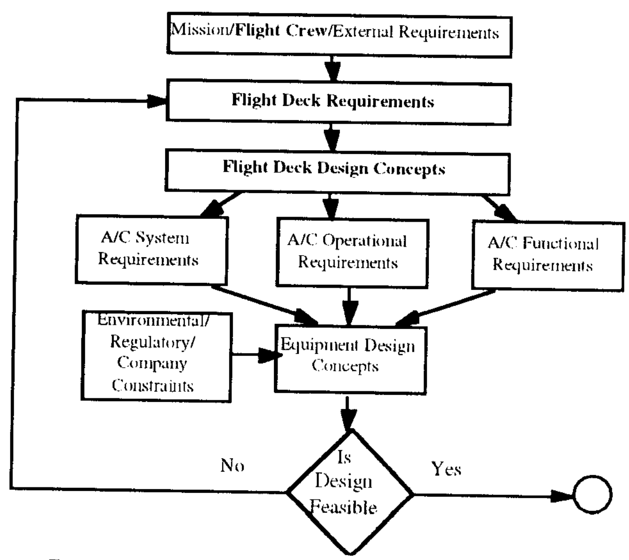

Figure 2: The *Wings* flight deck design process