Understanding the Role of Human Error in Aircraft Accidents

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The commercial aviation industry has achieved an enviable record of safety, but accidents still occur. In roughly two-thirds of aircraft accidents, aviation's human link receives the blame, and the proportion of accidents attributed to human error has not changed appreciably in 20 years. Most human error that leads to accidents surfaces in the performance of flight crews and air traffic controllers. The strategies used to address human error can be placed in two categories: introduction of technology that reduces the role of humans in the system and changes to the system and training suggested by human factors considerations. The pursuit of these approaches has largely become distinct, but they are both characterized by several basic assumptions. Both technologists and human factors specialists attribute human error to human fallibility and accept in varying degrees the inevitability of human error. Both accept the notion that humans are the most unreliable element in aviation. Both place emphasis on flight crews and air traffic controllers. Supporters of both approaches hold doubts as to the value of the other; in particular, the technologists view human factors as being too untidy to be the basis of design. The system that fails in an aircraft accident can be divided into animate (human) and inanimate components. If assumptions are reconsidered, there are mechanisms by which the inanimate system can contribute to causing the human error that leads to accidents. There is a spectrum of possible accident causes between the extremes of entirely human error or entirely inanimate system malfunction. Current interventions are heavily weighted toward the human error end of the spectrum, but this paper suggests an additional approach to interventions that alleviates system problems that cause human errors.

The commercial aviation industry has achieved an enviable record of safety, but accidents still occur. The distribution of accident causes for the world jet air carrier fleet from 1960 through 1981 is as follows (*1*):

Causal Factor	*Percent*
Cockpit crew	70–75
Airframe, power plants, systems	13
Maintenance	3
Weather	5
Airport, air traffic control	4

The proportion of accidents attributed to cockpit crew error has not changed appreciably since these figures were assembled (*2*). The greater than 70 percent of accidents attributed to human error seems to be a strong indictment of human performance and a powerful motivator for research that would reduce the frequency of human error.

Within the field of human factors there are numerous efforts to prevent the commission of errors in aviation, as recently documented or proposed in *The National Plan for Aviation Human Factors*, jointly developed by FAA and other agencies (*3*). For example, cockpit resource management (CRM) is a philosophy that seeks to enhance the effectiveness of the cockpit team through increased cooperation. CRM is already integrated into the pilot training of most major airlines, and, for example, United Airlines acknowledged the contribution of CRM in minimizing the loss of life in the July 1989 accident in Sioux City in which the flight crew was forced to improvise procedures to cope with loss of directional control.

By far the largest effort to prevent human error (measured by funding, personnel, or industry support) is through automation that seeks to reduce the role of humans. These efforts are motivated by the availability of powerful new information-processing technologies and the premise that reducing the human element will reduce error. The most recent generation of large air transports incorporates automation for flight control, augmentation, and management (ascent, cruise, flare, and landing), as well as automatic throttle control and fuel load management. The National Airspace System Plan proposes to automate many air traffic control functions (*4*). For example, the automated en route air traffic control system will automatically detect and advise controllers on potential airspace conflicts; the controller would no longer be required to detect conflicts through mental projections of aircraft trajectories (*5*).

Human factors is receiving increasing attention in the design of systems, especially automation systems, but there remains a lack of communication between the engineering and human factors disciplines. System development (automation or otherwise) requires the integration of a number of specialties. Most systems interact with humans on some level (design, manufacturing, operation, or maintenance). Thus, human factors should be a consideration, but it is not now a major one. If human factors is addressed at all, it is usually through specialists who act as advisers to the design team. As outsiders, these specialists have difficulty influencing the final product. Often they are called in after the fact to approve the design, when changes are impractical. In contrast, the concerns of electrical, mechanical, and aeronautical engineers, among others, are not neglected. This arises from a (seemingly obvious) distinction between the importance of attaining precise electrical or mechanical functionality versus the imprecision of the "best" human system interface.

Human error has persisted. This paper proposes an alternative paradigm for understanding human error and an additional avenue (called soft deficiencies) to address it. The paper is motivated by questions that do not seem to be well addressed by the current approaches:

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- Why are the most highly trained, paid, and professional humans in the system blamed for a majority of accidents?
- Why are pilots blamed for 70 percent of aircraft accidents when they represent less than 5 percent of the aviation community?
- Why has the percentage of accidents caused by human error been so consistent over the past 20 years?
- Why has the design community been resistant to changes suggested by the human factors community?

The ideas presented in this paper are advanced as motivation for an alternative paradigm in addressing human error that addresses the previous questions. Some distinctions are semantic, but the end result is additional interventions to those already being attempted. The problem is a complex one, and research efforts are under way on many fronts. This paper is offered as but a first step in enhancing the current approach to human error. The presentation might be somewhat novel, but the definition of the problem will be familiar to human factors specialists. The paper is directed at those in the aviation community who are not already enlightened about the importance of human factors considerations in design. The central discussion of the paper, headed Soft Deficiency and System Design, provides a basis for intervention that can be carried out jointly by human factors specialists and engineers. Focus on soft deficiencies would provide these groups with a common language and goals that are now lacking.

As indicated by the title, the focus in this paper is on understanding human error. The discussion is on the system-level "macro" issues as opposed to a specific definition of the perfect human-machine interface. There is always trial and error, but identifying actions that will prevent human error requires an understanding of human error.

Human error has been the subject of considerable research over the years, and numerous studies and publications address the issue. A recent book by Reason, *Human Error*, (*6*) provides a comprehensive overview of what is and is not known about human error. Science has yielded numerous theories that classify and explain vagaries of human behavior. Although these theories offered some inspiration, they were not the basis for the findings in this paper. The problem is that they are all very complicated, and a complicated explanation leads to a complicated intervention. The understanding of human error discussed here is the intuitive understanding that drives decision making. Fortunately, this theory of human error is simple and provides simple interventions. The present effort makes no claim to furthering the science of human error. The intent is to identify approaches that would reduce the number of aircraft accidents caused by human error. For example, no distinction is made between error and mistake. The author considers human error to be the type of action identified as human error in accident statistics. The examples used center on cockpit crews and pilots, because pilot error is believed to be the principal cause of accidents, but other examples, such as air traffic control or maintenance, are possible.

A few other clarifications of terminology are needed. Managers, engineers, and others who advocate or are involved in the implementation of automation as a solution are referred to as technologists. A system is a composite of skilled people, procedures, materials, tools, equipment, facilities, and software that provides an operational capability. Human interaction with the rest of the system will be referred to as human system interaction. The discussion of systems is in terms of the animate (human) and inanimate components. For the sake of simplicity, the inanimate system is sometimes referred to as the machine component of the system, but it includes all of the inanimate elements identified previously. The intention of design is referred to several times when the capabilities of humans are compared with those of the rest of the system. Although machines, tools, and procedures might be designed with certain intentions in mind, it is not clear that there is a corollary intent in human design, which is the common limitations and capabilities of humans. Several other distinctions in the use of words are made as they appear in the text.

HUMAN ERROR AS HUMAN MALFUNCTION

The root of the perception that humans are unreliable lies in the intuitive understanding of human error. Humans often learn new concepts through analogies with what they already know. For example, humans can make intuitive assessments about atomic structure equipped only with knowledge of the solar system and the fact that the two are similar. The use of analogy is a powerful learning mechanism, but it is not without problems when the analogy does not adequately represent reality. Observation demonstrates that the analogy used to understand human error by managers, engineers, and perhaps even scientists who study human error is that human error is like malfunction. Like malfunction, human error is the result of faulty design or other weakness. Like malfunction, human error is itself a bad thing. As in malfunction, intervention for human error requires fixing or replacing the human. As in malfunction, the one who commits the least human error is the best. At the very least, this idea of human error is hard on one's self-esteem. This section will address why equating human error with malfunction is probably not appropriate and certainly not productive.

Machines malfunction but, strictly speaking, humans do not. Malfunction not only indicates that something went wrong, but it also implies that the outcome was not consistent with the intention of design. Malfunction is often descriptive of machine failure, because machines often do not perform within the intention of design. It would be presumptuous, however, to assume that humans do not perform within the intentions of design. Indeed, although human performance can be maladaptive and have adverse effects, the performance itself is always the result of combined innate and learned capabilities. What might a human do that is not consistent with the intention of design? Placing a hand in a fire and enjoying it would be a malfunction. Desiring a life without food and shelter would be a malfunction. However, humans do not do these things. No humans would keep their hands in a fire or go indefinitely without food unless there were an accumulation of experience that made those events desirable. In the latter case, there is no malfunction, because the human is responding appropriately to experience or immediate circumstances. Errors that result from excessive workload, overtaxing complexity, or long periods with low stimulus are also not malfunctions. Humans have limitations of endurance, cognitive abilities, and attention span that cannot be overcome. Similarly, when a jet engine's performance decreases after being in an "over-speed" condition, no one claims that the engine has malfunctioned. Malfunction is not a good analogy for human error.

The fact that human error is not characterized well by malfunction means that assuming so is problematic and unproductive. This is illustrated when the malfunction/human error analogy is taken further. Machine malfunctions can be the result of worn parts, faulty design, or misuse. Intervention might involve replacing parts, correcting the design, or retraining the operator. What are the analogies of worn parts, faulty design, or misuse, in the case of humans? "Worn parts" might be like old people, but replacing humans is more involved than replacing machines. For example, humans cannot be replaced piece by piece. Some may accept that human error is the result of faulty design, but few would claim knowledge of a better design. The idea of human error being the result of human "misuse" shows promise, but retraining the operator (the inanimate system) may not be so easy. The point is that the interventions suggested by the malfunction analogy are all dead ends, or nearly so.

The problem with the malfunction analogy comes down to one thing: humans cannot be "fixed." The medical field is in the business of "fixing" humans, but addressing human error does not usually involve medicine. Training and retraining is normally considered the "fix" for humans, but even this is not exactly correct. Training is not a "fix" because it is not repair of something that is not working. Training involves knowledge acquisition through the human ability to learn. Even though human factors specialists may not view themselves as fixing humans, this is an underlying reason why decision makers are often reluctant to fund human factors projects. Few are willing to predicate plans and expend dollars on the undefinable process of fixing humans.

HUMAN ERROR AS SYSTEM MALFUNCTION

An assumption is integral to the blaming of 70 percent of aircraft accidents on human error. The system that fails in an accident has both animate and inanimate components. Humans are highly dependent on the rest of the system. Even if the cockpit crew did not follow procedures or was not adequately vigilant, it is an assumption that the inanimate system did not cause the crew to act in this way. It is not satisfying to blame inanimate objects, but human performance is too dependent on the environment to automatically be held accountable independent of the environment. The evidence accumulated to support the conclusion of human error only proves that the human could have prevented the accident (i.e., through use of proper procedures). Proving that the pilot could have prevented the accident is not the same as proving that the pilot caused it.

This is more than an academic issue. Although there are always legal implications, the principal reason for determining cause is to identify actions that would prevent future accidents (7). Blaming 70 percent of aircraft accidents on humans has led to the current drive for automation, but if the system is causing the human errors, additional interventions might be warranted. Although the theory of automation (no human, no human error) sounds plausible, the reality is not. In reality, replacing humans is a very complex, time-consuming, and expensive process. In the end, something less than total automation is always the result, and humans are still left to fill in the gaps. These gaps are usually not the result of careful planning, but are those parts of the system that the designers found too difficult to automate. Humans may be left with a role for which they are even less suited, and may not be able to maintain the situation awareness that is necessary to take over when the automation fails.

Attempts to evaluate the suitability of automation are usually inconclusive. Technologists can always point to an emerging technology that will overcome any limitations identified. Artificial intelligence (AI) is now expected to further extend the role of automation and surmount any shortcomings in the current generation. The author does not intend to pass judgment on automation, merely to suggest the need for some "reality testing." Five years of designing automation systems and 6 years of studying AI makes the author suspect that automation may not live up to expectations and will always be waiting for a technology that is "just around the corner." It appears that humans are at a disadvantage because they are held more accountable (no one expects that an enhanced version will be available next year). On the other hand, the version that is already available could be used more effectively and is quite powerful.

Is it any more plausible that human error is caused by the system? Consider an accident whose cause seems to be a clear case of human error. The following excerpt is from a National Transportation Safety Board (NTSB) report (7):

> About 0734 e.d.t., on September 11, 1974, Eastern Air Lines, Inc., Flight 212, crashed 3.3 statute miles short of runway 36 at Douglas Municipal Airport, Charlotte, North Carolina. the flight was conducting a VOR DME nonprecision approach in visibility restricted by patchy dense ground fog. Of the 82 persons aboard the aircraft, 11 survived the accident. One survivor died of injuries 29 days after the accident. The aircraft was destroyed by impact and fire.
> The National Transportation Safety Board determines that the probable cause of the accident was the flight crew's lack of altitude awareness at critical points during the approach due to poor cockpit discipline in that the crew did not follow prescribed procedures.

The type of accident described is known as "controlled flight into terrain." It is still one of the most common types of accidents, in which, inexplicably, cockpit crews fly aircraft into the ground even though all instruments and warning systems function properly. These accidents are the apparent result of the cockpit crew's lack of situation awareness. Perhaps the crew did not notice a disconnected autopilot (even given flashing lights and bells) or misjudged altitude because they were distracted (even though they are supposed to read instruments and not judge altitude). In any case, how could the (inanimate) system have caused the human error that led to the accident? Specifically, how might the system have contributed to the diminished situation awareness of the pilots? The landing procedures required may be complicated and inefficient, leading the pilots to seek shortcuts. The ground proximity warning system may be activated so frequently (every landing) that they desensitize the pilots. The automated systems may lay the foundation for boredom. Deferred-maintenance items (identified by fluorescent tags on instruments) might distract the pilots' attention. Difficulty in reading instruments may cause the pilots to favor visual landings, causing overdependence on visual cues. The list could go on, but the one factor that prevents all of these from causing an accident is pilots' ability to remain vigilant.

Pilots are very capable individuals who are expected to remain vigilant, but consider the factors that contribute to vigilance. Personal traits may not be dominant. All of the elements identified previously work against pilots' vigilance. Positive factors are also conceivable. For example, awareness of a recent accident "due to lack of vigilance" will certainly increase the cockpit crew's efforts to remain vigilant. Taken individually, each of these might be ignored as insignificant "noise." The problem is that they are additive: each one requires additional cognitive processing by the crew. Pilots can discipline themselves to carry out procedures properly (even if they seem to be inefficient); they can remember what each aural warning means (even if approximately 15 of the more than 100 possible alarms sound every flight); they can entertain themselves when the autopilot is in control (for 98 percent of the flight); they can remind themselves that those instruments tagged by maintenance are probably not needed; and they can remember to trust their instruments during landings. They usually manage to do all of these things, but even if it were possible for some pilots to overcome all of these factors every day for their entire career, the probability that all pilots will do so is remote. Not only does vigilance vary on the basis of external factors, but also the amount of vigilance needed (to avoid an accident) varies, depending on the phase of flight or flying conditions, such as weather and congestion.

Figure 1 shows a block diagram of a mechanism in which accidents are a function of vigilance and flight conditions—specifically, pilot effectiveness and flight conditions. Pilot effectiveness is the combination of competence and vigilance. Pilot effectiveness and flight conditions can be viewed as stochastic (random) processes. This is not to say that they are totally random, because there will be typical distributions based on the aircraft and routes flown. Nonetheless, their status at any given time is random, because the sum of the factors affecting vigilance and the flight conditions at any given moment will be random. Figure 2 shows a hypothetical distribution of flying conditions and pilot effectiveness for a single flight. A relative scale is used. The graph shows deviation of conditions and effectiveness above and below normal. It illustrates that it is not the absolute level of effectiveness or flight conditions that are important but their relative levels. If the level of effectiveness drops below the level needed by current flying conditions, an accident (or incident) will result. In the case shown, the levels coincide during landing. Note that the crash did not occur during the most demanding

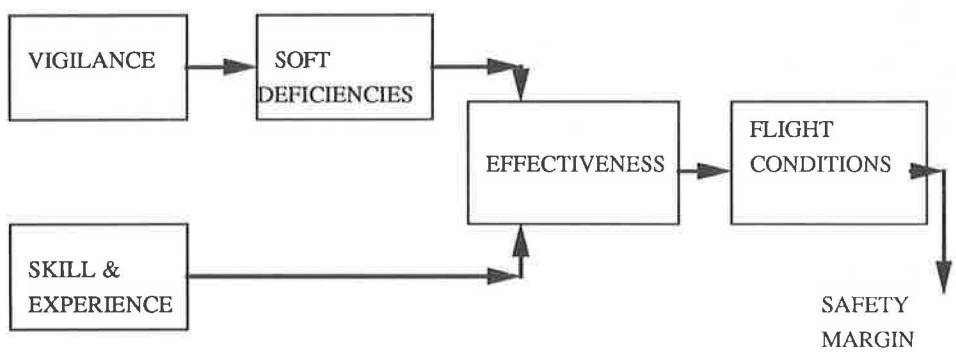

FIGURE 1 Mechanism for system design causing aircraft accidents.

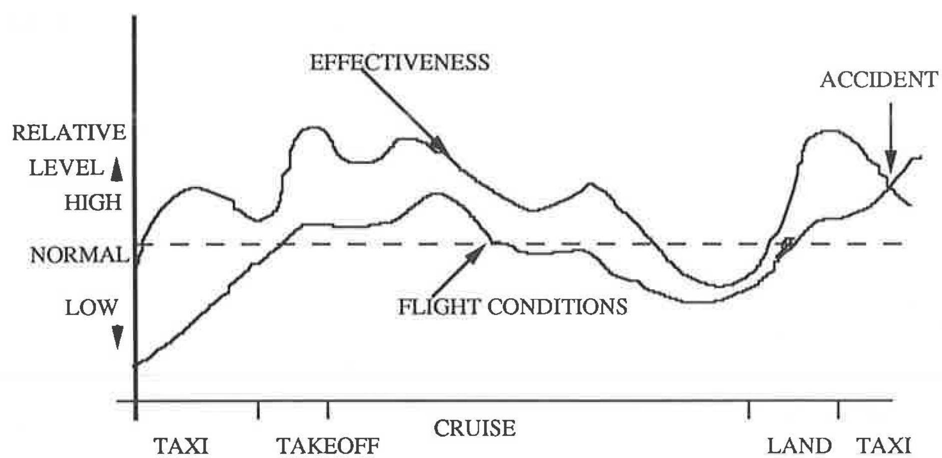

FIGURE 2 Hypothetical distribution of aircraft conditions and pilot effectiveness for a single flight.

flight conditions or while vigilance was lowest. It should be further noted that the time when two stochastic processes will coincide is also random. This model suggests a surprising conclusion: in effect, aircraft accidents are random events and are not necessarily a function of pilot performance. This at least is not contradicted by the findings of aircraft accident investigations. No one has ever shown a clear correlation between aircraft accidents and pilot performance. This will be discussed further.

Some additional terminology is needed. The factors affecting vigilance identified previously are labeled *soft deficiencies* by the author. Soft deficiencies are a broad class of system characteristics that work against human performance. Hard-system deficiencies (i.e., insufficient durability) cause the hardware to fail, and soft-system deficiencies (i.e., inefficient procedures) cause the human to fail.

All of the factors listed previously have contributed to the crash of Flight 212. The captain and the first officer had very good performance records and were experienced in flying this type of aircraft. The flight was the first of the day, and it is safe to assume that it was routine. The NTSB reference to "lack of altitude awareness" refers to the conversation between the pilots recorded during the last minutes of the flight. It seems that the pilots were looking for an amusement park tower they normally used as a visual cue to assess their position relative to the airport. The problem was that there was patchy fog and they were never sure whether they saw the tower. In their preoccupation with identifying the tower, they ignored the ground proximity warnings and did not adequately follow procedures. The reference to "poor cockpit discipline" refers to the crew's failure to follow procedures and to the fact that some of the conversation was on nonoperational issues.

The NTSB's pilot error cause and the author's soft-deficiency cause represent two ends of a spectrum. The crash of Flight 212 represents one failed landing out of many thousands, or perhaps even millions, of successful landings. Accepting that pilot error caused the accident requires accepting the fact that the crew of Flight 212 was an exception. It presumes that there was something unique about their lack of discipline. The mechanism of soft deficiency is largely independent of the crew. In this view, accidents are the result of external factors and need not be linked to pilot performance. Reality probably lies somewhere in between. The question is, where? It is not possible to know directly, but interventions based on the exception side of the spectrum are already being applied. It might be time to consider additional interventions suggested by the alternative.

HUMAN FACTORS

The field of human factors seeks to apply the knowledge of human limitations and capabilities (design intention) to the design of systems (*8*). The goal is systems that are compatible with humans. The field of human factors has been in existence for more than 40 years, and a great deal is now known about the limitations and capabilities of humans. Yet aviation systems (or systems in general) that are compatible with humans are the exception (*3*). One reason may be that there are still a few elements missing before consideration of human factors can become an integral component of system development. The missing elements might be the following:

- Conviction that human performance can be reliable.
- Causative linkage between aviation accidents and human system incompatibility.
- Clear interventions for ensuring human compatibility.

Naturally there is a diversity of opinions on these points, but the dominant consensus is the following:

- Humans are unreliable, and design for compatibility is secondary to automation, because human behavior is unpredictable no matter what the design.
- Aircraft accidents are caused by human errors that are the result of a lack of discipline. Aircraft systems sometimes do not help the situation but cannot be blamed for human fallibility.
- Human factors are too "fuzzy" to be used as the basis of design. It is impossible to say anything conclusively about interventions, given individual human differences.

Although definitive proof is beyond the scope of this paper, the arguments presented in the previous two sections take aim at the first two elements;

- Humans do not malfunction; thus, if system design is compatible with human capabilities and limitations, humans are completely reliable.
- Aircraft accidents are caused by the accumulation of soft deficiencies. Soft deficiencies are the elements of the environment that work against the pilot's vigilance. Soft deficiencies are the result of system design that inadequately considers human capabilities and limitations.

In the remainder of this paper, the author addresses the third point.

First, though, a few additional words on human factors are necessary. The author is told that the primary obstacle to interventions based on human factors is the complexity of human behavior and individual differences. Actually, complexity and individual differences present an obstacle to predicting the precise nature of individual human behavior but not to the design of systems that are compatible with humans. Observation of humans in most situations rapidly demonstrates the complexity and unpredictability of human performance (e.g., observing cockpit crew interaction, even when the high-fidelity simulator scenario is repeated). Yet from other viewpoints, human performance is very uniform. For example, humans share many common motivations, such as the pursuit of nutrition, shelter, peer approval, respect, and self-preservation. Further, although there are individual differences, humans share the same basic cognitive and physical abilities. For example, unlike computers or machines, humans process information symbolically and have limitations of endurance. Humans are more alike than different. The characteristics that humans share are those that are innate (possessed at birth). But if all humans are similar, what is the source of the complexity? The answer is individual experience. Individual experiences are as unique as fingerprints. Behavior is a function of innate and learned (from experience) components. Complexity of behavior arises from the learned component. This can be directly observed. Complexity surfaces when there is more than one way or no clear way to satisfy innate motivations with innate capabilities. Life rarely presents situations in which innate motivations can be satisfied through innate capabilities; thus we rarely see uniform behavior. Consider a simple example. If 10 people are asked to get a kite out of a tree, they will probably apply 10 different techniques. On the other hand, if a ladder is put in place and the same assignment is made, chances are that all 10 will use the ladder. Variability of human behavior is the result of the application of experience to situations in which humans are forced to adapt. Everyone has similar inherent capabilities and limitations and the same innate motivations. Rather than trying to characterize all of the varieties of human behavior, then, one should simply recognize that if the system is completely compatible with human capabilities and limitations, behavior will be consistent. To take this a step further, the existence of variability in human performance in any given situation is an indication that the humans involved are being forced to adapt. In other words, inconsistent performance may be the result of faulty system design (insufficient consideration of human factors) and not human fallibility.

This discussion does not seek to prove that humans never make mistakes. Clearly, training will remain essential to increase human performance. The distinction is that training addresses the learned contribution of human performance and not innate factors. Humans will always lose vigilance in certain conditions. It is not sufficient for machines merely to perform within functional requirements; it is essential that those requirements be compatible with innate human capability. In any case, this focus on the system does not reduce the responsibility of the individual. Systems will remain dependent on individuals performing to the best of their abilities. Soft deficiency is recognition that "to the best of their abilities" is not always enough. The final two sections of this paper address the concern that there are no clear design interventions suggested by consideration of human factors.

THEORY OF HUMAN FACTORS

Clear and concise guidelines for intervention require a theoretical foundation. The field of human factors has accumulated a considerable body of knowledge about human capabilities and limitations, but these do not yet form a theoretical basis. A theory is a system of assumptions, accepted principles, and rules of procedure devised to analyze, predict, or otherwise explain the nature of behavior of a specified set of phenomena. Electrical engineering is based on theories about electricity. Aeronautical engineering is based on the theory of aerodynamics. But the human factors system of assumptions, accepted principles, and rules of procedure used to analyze and predict does not adequately explain the behavior of humans. Until it does, human factors will not be incorporated in system development with priority equal to that of the disciplines that have a theoretical basis.

Fortunately, the addition of a few more assumptions and consideration of soft deficiencies is all that is needed to round out a theory of human factors. The assumptions needed have already been alluded to: (a) humans are reliable (i.e., performance is completely consistent with design intention) and (b) innate human behavior is uniform (i.e., variability in human behavior is the result of applying individual experience in situations in which humans are forced to adapt). These are, perhaps, impossible to prove and are thus assumptions, but the current consensus identified in the previous section is also an assumption.

The inanimate system is currently given the benefit of the doubt in cases of human error. As it stands, humans are expected to adapt to the limitations of the rest of the system. It seems more appropriate that systems should be designed to adapt to humans. Actually, this is academic, because the history of aircraft accidents demonstrates that humans cannot adapt sufficiently to the inanimate system, no matter how hard they try. The continued struggle of highly trained and professional commercial pilots should leave no doubt about this. Existing capabilities of system development hold great promise for the design of systems compatible with humans, but it will require a new way of perceiving the human component of the system.

The addition of these assumptions gives human factors a true theory capable of explaining the nature of the behavior of a specified set of phenomena. The behavior of interest is innate human behavior, and the specified set of phenomena is human system interaction. The claim can be made that human error can always be traced to some element in the system. This is not unlike the operative claim now used by technologists that all human error can be prevented by automation. Neither statement has value in a literal sense, but both are hypothetically plausible and ensure that perseverance will eventually lead to a solution. The only question is in the level of perseverance that will be cost-effective. As it stands, the human factors perspective allows attribution of performance irregularities to the complexity and unpredictability of humans. This says that the tools of human factors are not sufficient to understand all aspects of human performance. In effect, the outcome will still be a matter of chance. This may be reasonable and true based on the current assumptions, but it is not what a decision maker wants to hear. The implication is that funding of human factors projects is a gamble, because there is a possibility that no matter what the duration of the project is or its success, error may still persist. This may start to explain the disparity between the funding of human factors and automation projects.

The challenge does not just involve developing quantitative criteria. For example, the bulk of the information used by electrical engineers to design systems is qualitative. Design is based on guidelines for elements such as circuit function, layout, grounding, cooling, packaging. Engineers become skilled in design only through experience, because much of what is required cannot easily be conveyed in a text. Nonetheless, the impact of this qualitative aspect of engineering design on the performance of the final product is very clear in terms of cost of fabrication and reliability. This knowledge is what separates new engineers from veterans. Soft-system design will probably also involve a combination of quantitative and qualitative knowledge.

SOFT DEFICIENCY AND SYSTEM DESIGN

Relative to human performance, system design currently comes into question most often where there is a direct link (e.g., a case in which an instrument's location facilitates accidental engagement or disengagement) (*9*). The pursuit of soft deficiencies will be much broader. A candidate for soft deficiency may be any aspect of the system that is incompatible with innate human motivations, capabilities, and limitations (physical and cognitive). Previous examples suggest some changes in the cockpit that might make it easier for the pilot to remain vigilant. The solutions are not sophisticated; the difference is a matter of emphasis or priority. Requiring humans to adapt to the "minor" inconveniences of the system will no longer be standard operating procedure; system design should adapt to humans, or at least explicitly recognize where adaptation is not feasible.

The concept of soft deficiency is designed to facilitate the process by placing under one heading a broad range of human system incompatibility issues. Soft deficiencies must be pursued jointly by human factors specialists, engineers, and others. Thus, disparate disciplines are provided with a joint language and goals. Pursuing soft deficiencies will be fundamentally different from focusing on human error. Human error is no longer the problem; human error is a symptom of the problem. Soft deficiency provides motivation for "human centered design" beyond the desire of not being second to a machine. Automation should be implemented as a tool to make the system more compatible with humans, not as a replacement for humans. The existence of human error in system operation has implications for system design first and training second.

The search for soft deficiencies can start in those elements of the system that are vulnerable to lapses in pilot discipline. A number of soft-deficiency examples and potential interventions are listed below. The examples are already the subject of in-depth investigations, and the brief discussion here does not seek to provide definitive interventions. A complicated balance exists in the aviation system, and changes require thorough analysis and testing. The following examples are designed to highlight the alternative perspective and potential interventions suggested by consideration of soft deficiencies. A central theme of the examples is that improving pilot performance should be the intervention of last resort. All of the examples focus on errors committed by pilots (most have been identified as the cause of one or more accidents), but all the examples have interventions independent of pilots.

Example 1

Human Error

Pilots occasionally ignore aural warnings and flashing lights that indicate important conditions.

Soft Deficiency

The warnings are issued whether or not the pilot needs to be notified. For example, the ground proximity warning sounds every time the aircraft passes through the elevation of 1,000 ft. Pilots are constantly turning off alerts that are superfluous (they are already aware of the condition). Thus, turning off alerts becomes relatively routine. It becomes automatic. Occasionally, pilots will turn off alerts without giving sufficient thought to the meaning of the alert.

Intervention

This dynamic has led to accidents that were blamed on pilot error (*7*). Recommendations made after accident investigations were designed to ensure that pilots paid closer attention to the alerts in the future. The soft-deficiency perspective suggests something different. It is only natural for humans to become insensitive to repetitive stimuli. A change in the alert system is warranted: the alert should activate only if the pilot has demonstrated a lack of knowledge about the condition. There are numerous ways to achieve this. One approach might be to modify the alert circuit so that the pilot could turn off the alert during a window before activation. Then, for example, if the ground proximity alert ever were to activate, it would explicitly represent the pilot's lack of awareness.

Difference from Current Practice

This intervention recognizes that alerting the pilot is not simply a matter of sounding an alarm. Current alarms are incompatible with humans in two ways. First, the alarms activate too frequently. Activation when the pilot is already aware of the condition is a false alarm. Too many false alarms lead the pilot to ignore the warning. Second, cognitive processing is necessary to identify the meaning of the alarm. Pilots may lose their motivation to do the processing (too many false alarms), or there may not be enough time to do the processing.

Example 2

Human Error

Pilots occasionally fail to maintain situation awareness.

Soft Deficiency

Boredom is a known problem during long automated flights (*4*). While actively flying the aircraft, the pilot necessarily does whatever is necessary to maintain situation awareness. When the autopilot is in control, the pilot is less likely to work so hard to maintain situation awareness, and there may be lapses.

Intervention

Although it may not be possible to maintain a high level of stimulation in long automated flights, it should at least be recognized that automated flight is an adverse environment for humans. The system should facilitate mental activities that enable the pilot to remain aware. Maintaining situation awareness requires integrating information from a number of sources, and this involves considerable and continuous mental effort. The trick is to make it fun or at least interesting. Perhaps pilots could periodically test themselves. Perhaps the effort to maintain situation awareness could be incorporated into some sort of training. Perhaps small competitions could be set up between the pilots or between pilots and the automatic pilot. The point is to use innate human motivations (i.e., competitive spirit) or capabilities to offset other human limitations (i.e., attention span). No matter what is done, it should be possible for the crew to have nonoperational discussions. The long-run intervention may be to change the representation of flight information, so the pilot would not have to integrate information mentally from a dozen instruments.

Difference from Current Practice

Some work is under way to address this issue, but the principal intervention involves expecting pilots to stay more alert. Soft deficiency emphasizes the importance of facilitating the pilot's effort to stay alert.

Example 3

Human Error

Pilots occasionally fail to follow landing procedures (e.g., to call out certain altitudes during the landing cycle).

Soft Deficiency

The procedures are fixed and do not accommodate the possibility that the crew may not be able, for one reason or another, to carry out every aspect of the procedures. The procedures are rigid by design to elicit uniform performance. It is unrealistic, however, to believe that such uniform performance is possible. There are no guidelines for modifying the procedures, so it is left to the pilot to decide what should go and what should stay. It is inevitable that situations will arise in which the crew has to take shortcuts in following procedures. Policies and procedures should account for this.

Intervention

The intervention would be to leave intact the current requirements (which remain satisfactory for 99 percent of flights) but provide guidelines for adapting the procedures, when necessary. Pilots should learn the priority and motivation for each step in the procedure. It should become ingrained that missing an altitude call-out increases the risk of crashing short of the runway.

Difference from Current Practice

Current effort focuses on getting all pilots to carry out procedures perfectly during every flight. The soft-deficiency perspective suggests that this is unrealistic.

Example 4

Human Error

A pilot occasionally decides to seek visual cues in conditions that warrant using instruments.

Soft Deficiency

The information provided by instruments falls short of information available to pilots under Visual Flight Rules (VFR). Humans learn to fly under visual conditions and become accustomed to integrating the tangible and intangible stimulus of that environment. Instrument flying does not provide sufficient stimulus. Thus, humans inevitably favor visual cues.

Intervention

Flying an aircraft requires more than knowing heading, altitude, and velocity. It requires an integrated mental picture of the relationship between the aircraft, ground, and other aircraft. It requires skill and experience to develop this picture from existing instruments. Instruments should be designed to present information to the pilot that is closer to the information available during VFR.

Difference from Current Practice

Some effort is under way to improve pilot displays, but the principal intervention currently involves demanding increases in pilot discipline. The soft-deficiency perspective suggests reversing the priority of these interventions.

Example 5

Human Error

Pilots occasionally fail to maintain cockpit discipline or commit other lapses in professional conduct and standards.

Soft Deficiency

Cockpit crew conversations that have been recorded in the final minutes before accidents often are not focused on the immediate task of flying. Given the eventual outcome, it is disconcerting to see the pilots apparently disconnected from their duties. However, it is natural for humans to use casual conversation to reduce the monotony of day-to-day flying. Insisting that casual conversations be avoided will not achieve the goal of having pilots be more attentive to their duties. Pilots can monitor themselves on this account. Excessive dependence on discipline is symptomatic of other problems. Discipline is needed only when humans are expected to do things that they are uncomfortable doing.

Intervention

The cockpit environment, procedures, training, and policies should be revisited to determine what makes the process uncomfortable for pilots. Approaches that are more compatible with humans should be adopted. When improvements are not feasible, it should be recognized explicitly that a particular aspect of the process is incompatible with natural human behavior.

Difference from Current Practice

There is considerable focus on increasing cockpit discipline. The soft-deficiency perspective suggests that cockpit discipline is as good as it is going to get. Alternative interventions are needed. Alternative interventions are suggested by scrutiny of what is vulnerable to lapses in pilot discipline. Discipline is needed to make humans do things that make them uncomfortable, so these elements are thus prime candidates for enhancements suggested by human factors.

Summary

Expecting systems to take the blame for human error may seem to be an excessively burdensome requirement. It is a change of emphasis, but it probably will not result in a net increase of system complexity or cost. The additional design complexity caused by incorporation of human factors is balanced by a decrease in system objectives (it need not replace the human). Ambitious efforts to automate pilot duties contributed to costs for aircraft that have risen far faster than inflation. In any case, the idea is to integrate consideration of human factors and not to add steps to the design process. The army program MANPRINT (manpower and personnel integration) has integrated human factors into the acquisition process (proposal, selection, design, test, and evaluation). Although contractors were not initially enthusiastic about the idea, all found that the process did not lead to additional costs (*10*). It is important, also, to remember the reason for incorporating human factors in the first place (i.e., the payoff of enhanced system performance).

Systems are judged not so much by whether they meet functional requirements but by their reliability in meeting functional requirements. It has already been established that no system is 100 percent reliable. The proposal is to consider soft deficiencies in the assessment of system reliability. In other words, end the practice of distinguishing between system reliability and human reliability. The two cannot be separated in a meaningful manner. Although it will become more difficult for the system (human and machine) to achieve high levels of reliability, the term "reliability" gains more meaning. A machine might now claim to be highly reliable when its real-world performance, as a part of a system that includes humans, is poor. Reliability that includes human performance is more representative of reality than is hardware reliability alone. This version of reliability emphasizes that the human factors specialist is as integral to system design as the electrical engineer. Once this fact is accepted by all involved, it will promote cooperation, because neither can reach his or her goals without the other.

CONCLUSION

This paper presented alternatives to existing assumptions and suggested additional interventions to prevent the human errors that lead to aircraft accidents. The understanding of human error presented makes the case that human error is not human malfunction. Human error is not fundamentally different from human behavior that is not considered to be error. In both cases, human behavior is driven by attempts to satisfy innate motivations with innate capabilities. Unpredictable individual differences arise when humans apply experience in situations that require adaptation. Preventing human error is a matter of designing systems that do not force humans to adapt. The elements of the system that force humans to adapt are labeled soft deficiencies. Human factors effort should focus on the common innate elements of human behavior.

There are already examples of programs that successfully integrate human factors and system design. The army has one of the largest in its MANPRINT program, which links several aspects of the acquisition process and makes consideration of human factors a major evaluation issue. For example, system failure cannot be blamed on the skills of the soldier during test and evaluation, because system designers are aware of soldier skills during the entire design process. The initial apprehension of contractors is usually diminished by the end of the process, and the results have been very good. For example, the tools required to maintain one type of engine were reduced from 140 specialized tools and fixtures to a little more than a dozen that can be found in most homes. Yet there seems to be little indication that without government intervention companies will pick up the process on their own. Given the ideas in this paper and the success demonstrated by MANPRINT, there is hope that a process of education might turn the situation around.

Progress in this area should not pause for a debate on whether human error or the system causes aircraft accidents. Given that both require assumptions, the debate could be sustained indefinitely. Aviation does not have forever. Not that aviation is unsafe, but the shear number of aircraft expected to be in service means an increase in accidents. The increase might be sufficient to further alarm a public that already is not particularly comfortable with flying. There is room for both viewpoints. Considerable effort is under way based on interventions suggested by human error, and additional interventions suggested by system design are warranted.

There is a need to further solidify a theory of human factors, but the first step is one of awareness. The more people who can be educated about the importance of human factors, the more resources that will be available to develop a theory. The human factors community understands the problem and can evaluate the ideas in this paper. However, the Human Factors Society has a membership of around 5,000, and the Institute of Electrical and Electronic Engineers has more than 300,000 members. Other design organizations boast similar membership numbers. The greatest education challenge is in the design community. The author will begin the process by presenting the ideas initiated by this paper to design-oriented forums. If there are readers who are interested in volunteering ideas and knowledge or combining efforts in support of this education process, please contact the author.

One issue not addressed in this paper is perhaps the most difficult obstacle to the incorporation of human factors in system design. It is the difficulty of assessing the value of changes suggested. Soft deficiencies do not become readily apparent until the system is operational, and even then debate is likely. How does one know which soft deficiencies are tolerable and which must be addressed? In any case, once a system is operational it is too late for the changes to be cost-effective. The objectives of this paper are ambitious, but not so ambitious as to expect to solve this issue. The concepts presented are designed to broaden the acceptance of human factors in design and to establish a framework for addressing this issue. Once the design community is willing, the resources necessary to address this issue can be brought to bear. This paper represents one step in the journey to the higher system performance that can be attained when systems are more compatible with humans. Further progress will require the cooperative effort of the entire community. One of the greatest strengths of humans is the ability to solve problems. Now that we are agreed on the problem, it surely will be solved.

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