NASA 51-54 125044

N93-14614

VOYAGE TO MARS:

A CHALLENGE TO COLLABORATION BETWEEN MAN AND MACHINE

Irving C. Statler, Ph.D.
Aerospace Human Factors Research Division
NASA Ames Research Center
Moffett Field, CA 94035, USA

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Irving C. Statler, Ph.D.
Aerospace Human Factors Research Division
NASA-Ames Research Center, Moffett Field, California, USA

ABSTRACT

The missions of the Space Exploration Initiative (SEI) will support the participation of humans in the exploration of space beyond Earth-orbit, starting with a Lunar-base and eventually leading to a manned mission to Mars. These missions pose a new challenge to the designers of machines with which humans will be required to interact, particularly when those machines have certain attributes that might be considered intelligent. I speak about this concern and the need for a new philosophy of design from the perspective of my current position as the Manager of NASA's Project on Human Factors of Space Exploration.

For the foreseeable future of NASA's program in space, there will be very few activities or missions that will be accomplished entirely by autonomous systems without human involvement. We will rely on humans for all critical decisions, and on intelligent utilization of the limited human resource to ensure safe, reliable, and effective performance of the space exploration missions. The Mars manned-spaceship entity must be an integrated man-machine relationship of shared responsibilities in which the psychological needs, as well as the physical capabilities and limitations, of the human must be considered as fixed constraints in the total system design. The authority and responsibility for mission success will reside with the crew, but we will be expected to prove the ability of the total <u>human-machine system</u> to perform its task.

The concerns that I address in this lecture relative to designs of automated and intelligent systems for the SEI missions are largely based on the experiences we have had with integrating humans and comparable systems in aviation. We now have advanced systems and devices onboard our modern aircraft that permit virtually full automatic flight from shortly after takeoff through landing rollout, with increased precision and decreased flight crew workload. Generally, these high levels of automation and "glass cockpits" have been well received by the piloting community. However, several accidents, and a large number of the reported incidents, have been associated with, and in some cases appear to have been caused by, aircraft automation, or more properly by the interaction between automation and the human operators of aircraft.

We have already learned, for example, that automation is not an easy way to remove human error from the system. Our experience with automation indicates that its introduction usually relocates and changes the nature and consequences of human error, rather than removing it. We now know that the new errors created through automation can, in fact, be worse than the types of errors alleviated through automating. The evidence of problems of human interactions with advanced cockpits has become so pervasive that the FAA's new National Plan for Aviation Human Factors assigns highest priority to encouraging the development of "human-centered" design for automation and recommends the development of procedures for evaluating human factors issues as part of every major system development.

For the SEI program, systems that rely on integrated automation and robotics with humans permeate the arenas of vehicle maneuvering; vehicle servicing in space; in-space and surface assembly and construction; planetary rovers; surface operations; extravehicular activity and exploration; sample acquisition, analysis, and preservation; and scientific probes and penetrators. We are faced with the problem of designing a variety of systems in which a machine and a human will be expected to work together as partners, producing a symbiotic integration of the powers of the human brain and computers. Unfortunately, we have little appreciation of either the potential or the limitations of close working relationships between humans and intelligent machines, or of how these interactions affect relations with other crew members or total crew performance. We do not know how to design a non-human intelligence in such a way that it will fit naturally into a human organization. We do not, at the present time, have a rational, predictive methodology for system design by which the developer of the artificial intelligence subsystem can integrate human-factors principles with other system-design principles at an early stage in the development process. In order to realize the objectives of human exploration of space, we will need to learn how to integrate humans with machines to an extent far beyond current understandings, and we will need a new philosophy of design.

Currently, we continue to base designs on concepts that are, in one way or another, largely based on allocation of functions between man and machines even though this approach has been shown to be inadequate. The classical situation of human factors has been that some machine has been developed to do some task, and the human-operator aspects of controlling this machine and of being trained to do so have been dealt with in due course. The human in between the displays and controls has been used as an adaptive mapping that relates the interpreted displays into the appropriate control actions. This concept has been carried over into the designs of the most advanced automated systems. There has been a tendency to exploit that which is technologically feasible, leaving to the human pilot those remaining tasks which have escaped automation, together with whatever new tasks are generated. This design philosophy will never enable us to design machines with assurance of safe and reliable human interaction.

In this paper, I discuss a new philosophy for designing automated and intelligent systems based on thinking of a total system composed of human and non-human entities, whereas current concepts of the system include only the non-human entities and exclude the human entities. It is the "mutual influences" among the entities that constitute interactions, and system effectiveness is concerned with optimizing the interactions, and not the individual behaviors. The design philosophy is based on a concept of building a human-complementary, human-interactive system. In this philosophy, the allocation of tasks between men and machines becomes a meaningless concept. We are forced to think about a task that can be done by men <u>and</u> machines working together in a partnership. I describe how this design philosophy relates to an understanding of coordinated human activity, like that of the flight crew of commercial transport that has been the subject of studies at NASA-Ames for many years. Just as in a team of human performers, proficiency of the individual entities is no assurance of proficient and effective team or system performance.

Another concern that I address is that, in the current design philosophy, human-machine interaction is considered to be merely one of interface design. This viewpoint is superficial and a dangerous oversimplification. Artificial intelligence is going to be used to support dynamic interactive tasks in which the human mind is an important and active component of the total system. Designing tools for this kind of interaction is a cognitive activity. One cannot simply build a stand-alone intelligent system and then decorate it with human-computer interface features, and expect to achieve meaningful cooperation between the human and the machine. Certainly, interface design is an important element of the integrated human-system design, but the interactions must be well understood before undertaking an interface design.

In my design philosophy, computers and humans can both be viewed as information-processing systems capable of independent intelligent behavior. Consequently, understanding human-computer interaction necessarily involves understanding the individual processes of cognition of both parties as well as the even more complex processes resulting from attempts at their coordination and interaction. Our current research on computational modelling of human perception and cognition will enable us to describe the complementary contributions of human and machine to a system in order to be able to address human factors issues during the conceptual design stages of missions and systems. Using these models, we have already been able to develop protocols for enhanced and reliable human performance of tasks through proper selection of stimulus and response modalities that avoid cognitive conflict. The agent architecture of our computational models enables us to begin to consider intermixes of human and non-human intelligence. With their continued development and validation, we will use these computational models in simulations to develop guidelines for designs of missions, operations, and procedures, as well as intelligent systems.

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I. INTRODUCTION

A manned voyage to Mars is no longer a fantasy of authors of science-fiction. Almost certainly, the human who will first set foot on the surface of Mars is alive today. It is the inevitable next giant step for mankind.

In a speech commemorating the twentieth anniversary of the first lunar landing, President Bush announced a long-term continuing commitment to the human exploration of the Moon and Mars. The implementation of this Presidential commitment is NASA's program called the Space Exploration Initiative or SEI. The SEI will support the participation of humans in the exploration of space beyond Earth-orbit, starting with a Lunar-base and eventually leading to a manned mission to Mars.

A manned voyage to Mars means living and working in space for well over a year, isolated from Earth without any hope of help in an emergency. Within a week after launch from low-Earth orbit, the Earth will appear to the voyagers to Mars to be smaller than does the Moon seen from Earth. A couple of months out, the Earth will be a tiny black spot as it passes across the disc of the Sun. Communications with Earth will be very inconvenient with transmission delays of several minutes. The detachment, the severance of Earth ties, will seem quite complete to our Mars spacecrew. For some crew members, life in the confinement and isolation of the Mars spaceship may be characterized by fatigue, moodiness, disturbed sleep, sensory deprivation, lack of privacy, monotony, and loneliness as well as the constant possibility of life-threatening dangers or crisis situations. Cooped up in tiny, noisy quarters with others from whom there is no escape, the irritation with each defect in the setting increases with the time it must be endured. Analogous experiences of submarine crews on long-duration submerged patrols, Antarctic-based personnel, participants in underwater habitat experiments, and the US and Soviet manned space experiments have all shown effects of high emotional stress in the forms of apathy, depression, insomnia, hostility, boredom, and a consistent decline of motivation. Intense fear produces a temporary loss of perceptual acuity and perceptual-motor coordination, a narrowing of attention span and range of perceived alternatives, reduction in problem-solving and decision-making capabilities, oversight of long-term consequences, and inefficiency in information search. Effects such as these on any single member of a group will influence group functioning. It may be fair to question whether a human crew can survive such a journey, much less remain productive. Nevertheless, our Mars voyagers must arrive at their destination in good physical and mental condition ready to go to work in the 1/3 gravity of Mars after 8 months of weightlessness --- without any hope of assistance from the local inhabitants. (Ref 1)

There are a great many questions to be answered about the physiological, psychological and behavioral effects of such a mission on the human crew before we will be able to ensure their safety, reliability, and productivity. In this lecture, I propose to address only one small, but very significant, part of this scenario. I am concerned about the design of the systems with which the crew will need to interact in order to perform these extraordinary missions. I am concerned because, as the Manager of NASA's Project on Human Factors of Space Exploration, I have assumed a certain personal responsibility for the crew's safety and productivity. The purpose of this paper is to tell you of my personal perceptions of some of the issues confronting the designers of the machines with which humans will be required to interact, particularly when those machines have certain attributes that might be considered as "intelligent". As I do not accept the connotation of intelligence when applied to machines, I prefer to speak, for the most part in this presentation, of various degrees of automation, rather than intelligent systems. All automation might be viewed as exhibiting some aspect of intelligence, but artificial or machine "intelligence" is quite different from human intelligence, and it serves no useful purpose to try to relate one to the other.

The Mars spacecraft will be a living entity adapted for survival in space independent of Earth; a symbiosis of humans and machines functioning autonomously. There will be very few activities that will be accomplished entirely by autonomous systems without human involvement. The Mars manned-spaceship entity must be an integrated man-machine relationship of **shared** responsibilities. The authority and responsibility for mission success will reside with the crew, but we will be expected to prove the ability of the total <u>human-machine system</u> to perform its task.

My concerns about the designs of automated systems for the SEI missions are largely based on the experience we have had with integrating humans and comparable systems in aviation. The demands of the aviation system have motivated much of the automation we now take for granted. (Ref 14) I do not intend to appear critical of the enormously capable aircraft flying safely today; however, just as other fields traditionally look to aviation for technological leadership, Human Factors researchers can learn much that is relevant to design of space systems by examining the history, the developments, and the problems of modern cockpit design and operational aviation experience.

II. YESTERDAY

The history of human factors in machine design has been that a system is developed to perform some mission or task, and the human-operator aspects of controlling this machine and of being trained to do so have been dealt with in due course. For the first few decades of aviation this approach worked fairly well for aircraft design, because we could rely on the adaptability of the human. We could take advantage of each new technology as long as the human perceptual capabilities were sufficient to provide all the information he needed to operate the system reliably. Things started to change dramatically in our military fighter aircraft during the late '40's and early '50's. These aircraft were assigned a greater variety of missions each of which had become increasingly more complex. Automated devices were required to make flying the higher-speed aircraft easier, but these required more displays to enable the pilot to monitor their performance. More and more information had to be presented to the pilot to enable him to make the decisions and to operate the systems necessary to accomplish all these missions. The reliance on instrumental information increased while, at the same time, the number of instruments increased. Over the next few decades, electro-mechanical instruments, switches, and buttons propagated wildly in the cockpit, filling all the available space. Unfortunately, the aircraft also became slimmer and the space available in the cockpit for displays diminished. Fortuitously, the technology for computer-generated displays and computer-mediated controls became available in reasonable sizes, power requirements, and cost. The cockpit designer's solution to his dilemma was to replace the task-specific displays and controls with multi-purpose displays and multi-function controls. This solved the narrowly defined display problem, but the computers that were brought aboard to drive these displays were capable of presenting far more data than a human could possibly access and assimilate in real time—and designers began to make full use of that capability. The cockpit of the F-18 aircraft is one of my favorite examples of the data overload produced by the display designers of that era.

The F-18 cockpit has three cathode-ray tubes and a head-up display. There are 675 acronyms and 177 symbols that can appear in four different sizes on any of the three cathode-ray tubes. There are 73 threat, warning, and caution indicators, 59 indicator lights, and 6 warning tones (no messages, just tones), 10 multi-function switches on the throttle, 7 on the stick, 19 controls on the panel underneath the head-up display, and 20 controls around the periphery of each of the three cathode-ray tubes, each of which has a multi-switch capability. Most of the data displayed requires that the pilot's foveal vision be engaged (while peripheral vision, a valuable communication channel in earlier displays, is largely ignored). Every piece of data that is available to the pilot through the multi-purpose displays requires an additional control to access it. This requires the pilot to remember how to access the desired data and how to perform the necessary sequence of control functions. Often, these controls must be found and actuated by touch while the pilot is visually engaged elsewhere, sometimes during moments of extreme physical and mental stress. Concomitantly, as not all of the information about his aircraft could be displayed to the pilot at all times, there evolved a proliferation of warning and alerting systems. These systems reminded the pilot to take actions, call attention to deviations from expected ranges, suggest or demand an action, warn of unacceptable configurations, and even take action on their own. Voice and other aural displays and even tactile displays were introduced in an attempt to increase the number of physical channels available for transferring all these data. However, we learned that the addition of a secondary modality does not double the human's information processing capability; indeed it may even impede it by distracting the operator at a critical time. In fact, the operator may not even be aware of additional information regardless of the modality because humans, under high-stress conditions, tend to narrow their attention. To make matters worse, the human tendency in stressful situations is to see what he expects to see and hear what he expects to hear.

The problem was further exacerbated by a traditional development process in which the aircraft flight controls and the cockpit displays were designed in separate departments that seldom communicated with one another. The human in between the displays and controls was used as an adaptive mapping that related the interpreted displays into the appropriate control actions. While the display designers were concerned with things like ambient lighting, viewing angle, luminance, contrast ratio, font size, color, resolution, wave length, and finding space in the crowded cockpit, the flight-control engineers were separately interpreting the test pilot's Cooper-Harper ratings into terms of aircraft design parameters to establish requirements for automation and augmentation of its stability or control characteristics.

Neither was paying much attention to the informational needs or the perceptual and cognitive limitations of the pilot. Consequently, problems at the human-machine-systems level were discovered only during operation or, at best, during flight test or man-in-the-loop, ground-based simulation late in the system development.

We found that the electronic display systems we provided to aid the pilot sometimes were not helping at all, and were actually complicating his job. The pilot was frequently being confronted with too much data in formats that were not conducive to rapid interpretation and integration, and whose access imposed a memory load. Some applications of computer interface technology resulted in increased demands on the slow, deliberative, capacity-limited human cognitive processes rather than in engaging parallel, automatic, perceptual-recognition-based processes. The pilot was often drowning in data much of which may be essential to his survival, but was starved for information. Unfortunately, most of these technological advancements in automation and displays, and their concomitant problems, were not confined to the cockpits of military aircraft; they also appeared on the flight decks of commercial air transports, in submarines, nuclear power plant control rooms, battle command and control centers, space launch and mission control centers, and, even, in surgical operating rooms.

It may still come as a shock to some designers (although it should not surprise this audience) to learn that the human-machine performance, and the Cooper-Harper ratings, can be influenced by changes in the designs of <u>either</u> the displays <u>or</u> the controls. (Ref 2,3) Lebacqz and Aiken showed that there exists a trade off between control augmentation complexity and display presentation sophistication, and that the trade off is a function of the task being performed. Furthermore, (with all due credit to my good friends George Cooper and Bob Harper for the admirable original intent of their rating system) pilot opinion expressed as Cooper-Harper ratings cannot be used to design systems because the pilot cannot, and should not be expected to, identify the particular feature of the display-control system to which he is reacting. From the point of view of the human in between, the issues of displays and controls are not separable.

<u>III. TODAY</u>

In 1920, the Air Service News Letter No. V1394 on "General Rules to be Observed at all U.S. Flying Fields" said "do not trust any altitude instrument". We have come a long way to an era when on-board computers automatically execute precise vertical navigation maneuvers. Today, computer technology has made possible levels of automation which existed only in science fiction a short time ago. The modern aircraft is heavily automated and multiple color computer screens in the "glass cockpit" on the modern flight deck show maps, instrument readings, and even procedures.

Before going further, let me clarify a current confusion. The term "glass cockpits" is often used interchangeably with automation when, in fact, they are not synonymous. The widespread use of cathode ray tubes (CRT) on modern flight decks to replace the array of electro-mechanical gages and dials has led to the use of the term "glass cockpit". However, conventional instruments have been converted to computerized displays on CRT's without necessarily introducing any changes in the degree of automation. Also, autopilots of one sort or another have been introduced into aircraft without any significant changes in the displays. In fact, the first concepts for autopilot control were proposed before the Wright brothers flew. In 1891, Hiram Maxim patented a gyroscopic "stability augmentation" device that was meant to adjust the flight surfaces of a flying machine.

The Flight Management System (FMS) which first made its appearance about ten years ago, incorporates an entire flight plan and replaces the reams of navigational charts that are needed to cross the continental US (although the paper charts are still carried on board in case of computer failure). Advanced systems and devices on board our modern aircraft now permit virtually full automatic flight from shortly after takeoff through landing rollout, with increased precision and decreased flight crew workload. Moreover, these high levels of automation and "glass cockpits" have been well received by the piloting community.

Results of a survey of over 1400 pilots and engineers conducted recently by the RAF Institute of Aviation Medicine revealed enthusiasm for the advanced automated flight decks. (Ref 4) The pilots generally said they liked flying them, they were less tiring, and they were "controlling" and not merely "monitoring" or "managing" the automated system.

However, we have not yet accumulated sufficient experience to praise or condemn with assurance. These new aircraft are designed to work best "hands off" during nominal operations, and they are excellent in this mode. It is only when the pilot must take over in <u>off-nominal</u> situations that human factors issues ever come to light; but, these systems are designed to very high standards of reliability. Off-nominal situations due to system failures are rare, and most of the pilots who responded to the questionnaire never encountered one. Nevertheless, a number of incidents have already been reported that give us cause to take another look at the human-machine interactions of these modern aircraft. (Ref 5) The source of much of our information is NASA's and the FAA's confidential Aviation Safety Reporting System conceived over 15 years ago by my colleague at Ames, Dr. Charles Billings. (Ref 6)

We have learned from these reports that the introduction of automation has had unanticipated effects on human performance and has introduced new kinds of system faults. We have found that automation usually relocates and changes the nature and consequences of human error, rather than removing it. Despite the aerospace industry's success at developing ever more sophisticated and reliable technology, the percentage of human-error-related incidents and accidents has remained remarkably constant. (Ref 7) Recent figures from the FAA attributed 66% of air-carrier accidents, 79% of commuter fatal accidents, and 88% of general aviation fatal accidents to human error as a causal factor. However, it is only fair to point out that the human who erred was not always one of those on the flight deck; he may have been on the ground at the time or back at his plant where he designed the aircraft.

Several accidents, and a large number of reported incidents, have been associated with, and in some cases appear to have been caused by the interaction between automation and the human operators of aircraft. Flight crews have ignored (or have been unaware of) important instrument readings such as fuel levels, have failed to hear warning devices, have deviated from basic operational procedures, have shut down the wrong engine or thrown the wrong switch, have failed to coordinate crew activities, have apparently become totally disoriented, and have continued to rely on the autopilot when it clearly was not operating properly. Automation has acted in ways not expected or desired by the pilots. In some cases, automated configuration warning devices have failed or been rendered inoperative and flight crew procedures have failed to detect, by independent means, an unsafe configuration. In other cases, automation has operated in accordance with its design specifications, but in a mode incompatible with safe flight under particular circumstances. In still others, automation has not warned, or flight crews have not detected, that the automation was operating beyond its design limits or unreliably.

We have also received reports of incidents from commercial aviation that have been identified with too little workload in some phases of flight to the point of complacency, lack of vigilance, and boredom. Others have been associated with too much workload in off-nominal situations, particularly when the automated systems call for increased head-down operations during these times.

The computers introduced between the aircraft's state sensors and the displays and between the pilot's inputs and the highly automated control surfaces of the aircraft serve to obscure the pilot's image of his aircraft. Previously, displays and controls were both directly coupled to the aircraft so that the pilot was able to construct the mental image of the aircraft state directly from displayed responses to his control inputs. Today, engineers can easily and inexpensively incorporate logic into the airplane itself; but the computers introduce (by design or otherwise) dynamic mappings of their own so that the pilot is no longer able to relate the displays directly to the aircraft state or his control inputs to the aircraft's responses. The displayed data are not consistently related to the pilot's inputs. (Ref 8) Arbitrary delays, spatial separation of cause and effect, and discrete, discontinuous subsystems tend to obscure cause-effect relationships. The pilot is insulated from the aircraft and develops a completely different image of the system he is operating than he would if the computers were not there. Consequently, any failure of the computers (either due to electro-mechanical failure or an unexpected situation) requires the pilot to intervene in a system with which he is not currently familiar.

Intervention is further complicated by inadequate feedback to the operator about system status for timely diagnosis should an off-nominal situation occur. (Ref 9) Consider, for instance, the case of the race car that was equipped with the latest automatic compensation for brake failures. When it suffered a failure in one brake, the system automatically compensated, just as it was designed to do. Shortly after, a second brake failed, and, due to the increased loading caused by the compensation system, the third-brake failure quickly followed the second. But, the automatic compensation system had done its job so well that it was not until the fourth brake failed that the driver realized he had a problem. This might make a humorous anecdote except for what happened to the driver and the fact that there are several examples of similar incidents occurring in aviation. Consider the case of the China Airlines 747 accident in 1985 which experienced a gradual loss of power from its outer right engine. The autopilot compensated for the increasing tendency to yaw until it finally reached the limit of its compensatory abilities and could no longer keep the plane stable. At this point, the crew did not have enough time to determine the cause of the problem and to take action. More recently, a failed fuel pump on an A320 caused a gradually increasing unbalance that was quietly and efficiently compensated by the autopilot with no indication of a problem to the crew.

Recently, aircraft designers have begun to look at incorporating more and more "intelligence" into the automated systems as ways of augmenting (or replacing) human capabilities and, thereby, reducing the potential for human error. Artificial intelligence, decision-aiding systems, knowledge-based systems, and expert systems became the "buzz words" of the eighties. Today, we are considering proposals for military aircraft with one human pilot supported by several electronic crew members. I recommend a considerable dose of caution. While knowledge-based and expert systems have found some limited applications in the control of physical plants, manufacturing processes, and quality control, the majority of these systems have fallen short of the promise of competent performance. (Ref 10) While these systems can take over control that used to be done by people, they are not able to handle all abnormalities, nor are they able to provide the continual, appropriate communication with a human partner that occurs naturally among human team members.

A large part of the problem is that technically complex and sophisticated systems continue to be designed assuming the human operator will provide all the adaptive control and integration required for effective operation. The systematic consideration of human cognitive performance characteristics and limitations is not typically a part of the design of the aircrew station. There is little evidence that anyone has analyzed the role of the modern flight crew and designed the cockpit, the instrumentations, the procedures, and the controls around that role. The aerospace community still treats human error as a training or discipline problem, not as a sign of poor design or inappropriate procedures. (Ref 11) Bainbridge says " the designer who tries to eliminate the operator still leaves the operator to do the tasks which the designer cannot think how to automate". (Ref 12) The tendency to exploit that which is technologically feasible, leaves to the human pilot not only those tasks which have escaped automation, but also whatever new tasks are generated as a consequence of automation. Frequently, such systems only work in the most benign environments. Wiener has called such designs "clumsy" automation, but they are clumsy because they have not taken proper account of the characteristics of the human operator. (Ref 13)

We have learned that the new errors created through the current philosophy of design of automation can, in fact, be worse than the types of errors alleviated through automating. Egan found that there are dramatically greater individual differences in the performance of computer-mediated tasks, and suggests that most of the difference is due to a larger number of more costly errors inherent in computer tasks. (Ref 14)

While automation conveys very significant benefits, the aviation community clearly perceives in automation a potential threat to air safety. (Ref 15) Questions are beginning to emerge about the respective roles of humans and the new technology. Anecdotal reports of problems with automated systems are abundant, and mostly these have not been the results of failure in machine reliability, but rather of failure of information management and communication between the machine and the human operator.

The evidence of problems of human interactions with advanced cockpits has become so pervasive that the new US National Plan for Aviation Human Factors assigns highest priority to encouraging the development of "human-centered" design for automation and recommends the development of procedures for evaluating human factors issues early in the development of every major system. Also, the human factors problem has been recognized as cutting across all elements of the aviation system where the system encompasses the flight deck, the training, the operating procedures, the air traffic control system, the maintenance environment, the system designers, and the systems integration. (Ref 16)

A lack of understanding of and appreciation for the characteristics, needs, and limitations of human performance and behavior manifests itself today as mistakes in the designs of flight deck displays and controls, unrealistic procedures, excessive training costs, and a challenge to human adaptability. (Ref 17) The capability to model, structure, and analyze the human components of complex and interactive man-machine systems, has not kept pace with the current capability to develop advanced technology systems with which the human must interact. For certain, our experiences with automation in aviation give us cause to question whether the current design philosophy based on allocation of functions and reliance on human adaptability will suffice for designing the systems of the SEI missions.

IV. TOMORROW

All of the missions of the SEI will be performed by a composition of integrated technical, human-biological, and human-social subsystems. The operational envelope of these missions will be determined not only by the individual capabilities of each of these various subsystems, but also by their combined performance as a result of human interactions with other humans, with his environment, with the machines and equipments, and with the operational procedures.

For the SEI program, systems that will rely on integrating automated and robotic machines with humans permeate the arenas of vehicle maneuvering; vehicle servicing in space; in-space and surface assembly and construction; planetary rovers; extravehicular activity and exploration; sample acquisition, analysis, and preservation; and scientific probes and penetrators. Humans will need to interact reliably, safely, and efficiently with complex, automated machines during inspection, assembly, check-out, operation, maintenance, repair, and emergency intervention in order to perform the tasks of the exploration missions. The SEI missions will rely on intense interdependencies among humans and machines to an extent that is seldom encountered on Earth. To achieve the objectives of the Mission from Planet Earth, we are faced with the problem of designing a variety of systems in which machines and humans will be expected to work together as partners, producing a symbiotic integration of the powers of the human brain and computers. This is an incredibly complex and difficult challenge. It is quite likely that successful developments in these areas will pace the progression of the SEI missions from the Moon to Mars.

The Committee on Human Exploration of Space of the National Research Council, in its review of NASA's Report of the 90-day Study on Human Exploration of the Moon and Mars (November 1989), identified "Exploration Human Factors" as "Critical Exploration Initiative Technology". The "Review of NASA's 90-Day Study and Alternatives" published by the National Academy Press (1990) states that:

"Mechanical and computer-aided extensions of human (astronaut) managers can provide enhanced efficiency in inspection, assembly, maintenance, repair, and exploration tasks. The most powerful approaches to human exploration will integrate humans with machine systems to accomplish more than either can do alone.

"...<u>Advanced human/machine systems are not merely an enabling technology, but a requirement for practical HEI operations</u>. Technical advances can extend profoundly the human role as master of highly flexible human surrogates, but obtaining such potential benefits will require more than complex robotry and automation. NASA presentations based on the 90-Day Study implicitly recognize this by grouping operations in functional categories. Systems that integrate automation and robotics with humans permeate the arenas of vehicle maneuvering; vehicle servicing in space; in-space and surface assembly and

construction; planetary rovers; surface operations; extravehicular activity and exploration; sample acquisition, analysis, and preservation; and scientific probes and penetrators."

The recent Report of the Advisory Committee on the Future of the U.S. Space Program (the Augustine Committee report) also addressed these concerns. (Ref 18) While it does not specifically speak of Human Factors, there are statements regarding Life Sciences in most of the programmatic recommendations that clearly imply concerns for the behavioral and psychological, as well as the physiological, well being of the astronauts. The report of the Synthesis Group titled "America at the Threshold" specifically recognizes the criticality of Human Factors, and the need to design equipments and machines for compatibilty with human operators. (Ref 19)

So far, our approach to designing automated systems with which humans must interact has not been entirely satisfactory. Currently, the functional requirements for complex systems rarely specify even the information needed by the human operator to perform the task. (Ref 20) We shall be unable to implement rational designs for the systems we need to accomplish the SEI missions with assurance of safe and reliable human-system performance without an understanding of how to combine human and automated systems effectively.

Designs for effective human-computer interactions are further complicated by the effects of long-duration missions in space. We do not yet know the effects on crew performance of long-term isolation and confinement, or of long-term exposure to zero/micro/partial gravity or to artificial gravity. We do know that long periods of low-level interaction can result in decreased system productivity due to monotony and boredom of the human operator. We do not know how to keep crew members highly skilled at complex tasks that they seldom, if ever, have to perform. The impact of automation on crew performance in terms of vigilance, readiness, and the ability to handle system breakdowns and failures are not well understood. The most important functions aboard present day and projected spacecraft involve diagnosis and decision making, and our greatest gap in knowledge currently in task retention is in understanding the retention of diagnostic and decision-making skills. All of these factors must be taken into account in designing the systems with which the SEI-mission crews will interact. (Ref 21)

Also, the human-machine systems for the SEI missions must be designed according to a philosophy of human-centered automation because the effective authority and responsibility for mission success will rest with the crew. For the foreseeable future, it is unlikely that NASA would tolerate the fielding of a system that is capable of effectively overruling a crew member. Moreover, the human crew will demand that final authority. Automated systems will provide support for the crew's performance of critical tasks and must be designed to enable maximum flexibility in the crew's selection between complete automation and complete manual control in the performance of a given task, and so the problem area is that of partial automation.

Unfortunately, we have little appreciation of either the potential or the limitations of close-working relationships between humans and complex, automated machines, or of how these interactions affect relations with other crew members or total crew performance. We do not know how to design a complex, automated machine in such a way that it will fit naturally into a human organization. (Ref 17) We do not, at the present time, have a rational, predictive methodology for system design by which the developer of the artificial intelligence subsystem can integrate human-factors principles with other system-design principles at an early stage in the development process. The basic research has barely begun to explore even those human factors issues that have been evidenced in our aviation experiences. I am concerned that, without the appropriate design philosophy, the introduction of artificial intelligence subsystems can exacerbate the already extraordinary operational problems of the SEI missions.

V. A DESIGN PHILOSOPHY:

In 1947, Fitts and Jones stated; *"It should be possible to eliminate a large portion of so-called "pilot error" accidents by designing equipment in accordance with human requirements"*. (Ref 22) In 1951, Fitts, in a landmark paper, developed a list comparing the functions for which man is superior to machines to the functions for which the machine is superior to man. (Ref 23) Ever since that time, this list has been used for assigning duties and allocating functions between man and machines in designs of automated systems, but it does not work. While strides have been made in reducing the probability of some kinds of pilot error, the design philosophy based on allocation of functions between men and machines has not been successful in coping with the increasing complexity of modern aviation systems. All attempts to build and expand upon this concept have led to difficulties and contradictions. The facts of the Fitts list are correct and, yet, the concept has failed to produce reliable systems. The inutility of Fitts' list must be associated with its use as a basis for comparing man to machine and choosing the one that fits best to a required function. The problem is that men and machines are not comparable, they are complementary. (Ref 24)

We need a new philosophy for designing systems that are composed of human and complex, automated entities working together to accomplish a task. This philosophy must not try to compare men with machines in the competition for assignment of duties that the concept of allocation of functions has produced. Rather it must be based on ways to allow men and machines to complement each other. It must take into account man's perceptual and cognitive capabilities and limitations, rather than rely on his adaptability. I propose to construct a rationale for such a philosophy on the basis of my perceptions of the circumstances that will prevail in the development of the systems needed for the SEI missions.

Billings (Ref 15) views the relationship of human involvement and automation in aircraft as a continuum ranging from "Direct Manual Control" to "Autonomous Operation". I prefer to view the systems for the SEI missions as falling into one of the following three distinct categories:

<u>CASE 1</u>: A subsystem may be designed to operate automatically when
- a. all the features of the state of the world necessary and sufficient for all decisions to be made can be sensed, processed, and controlled with adequate accuracy by the machine alone; <u>and</u>
- b. the automatic system can be built with acceptable operational reliability (including in unpredictable situations).

When the task environment is predictable and a priori controllable, and when the activities necessary for the task are iterative and demand consistent performance, a machine can, and should, perform the task without continuous human involvement. The nominal operation of such subsystems can be made transparent to the human. These systems are nearly completely automatic, except that they must be designed to allow graceful intervention by the human operator in the rare emergencies, and for maintenance. Subsystems that fall into this category, for example, are the automated yaw damper on aircraft, the automatic choke in the automobile, and, very likely, the life-support systems for the planetary habitats. These are what Dave Woods et al call *"intelligent subordinates"*. (Ref 25) An important area for human factors engineering research that has been neglected is how to design a complex automatic system to facilitate its being backed up manually.

CASE 2: Humans will not require or rely on computer-based systems for assistance in making decisions when

a. human sensors (or direct access to human-compatible sensors) of all features of the state of the world necessary and sufficient for all decisions to be made are adequately accurate; and
b. there is adequate time for the human to make the decisions and take the actions with acceptable reliability.

When the environment is not predictable, or, if predictable, not controllable a priori, then man (aided by the proper tools) is required. A subsystem that falls into this category produces, at most, an interface design problem to put machine-sensed data into human-compatible displays. The personal computer and the automobile steering system fall into this category.

In practice, for the sake of safety and reliability, many subsystems will be designed to fall within one or the other of these first two categories. However, for space missions, these will not be sufficient to perform all the required tasks, and there will be a third case that I call partial automation into which most of the systems will fall.

CASE 3: Humans and machines will share information and will jointly exercise control when

a. there are situations in which the machine senses certain features and processes certain data while the human senses and processes others that are needed for the decision; i.e., information about the state of the world must be shared by the human and the machine to define its true state; or
b. there are situations in which the machine initiates some of the control actions while the human initiates certain other control actions all of which must be coordinated for proper performance; i.e., responsibilities for actions taken to change the state of the world must be shared by the human and the machine to achieve the mutually desired state.

I am limiting myself in this presentation to the situations that fall into this third category of partial automation because, from a Human Factors point of view, these represent the challenge of the future. Moreover, I am assuming that, for the the SEI missions, the human will be assigned the responsibility to manage, operate, and assure the safety of the system. Therefore, human-centered automation is the key to system effectiveness. Specifically, we need a philosophy of system design for the case when a human must rely on computer-mediated data from sensor hardware for a portion of the information (notice I did not say data) that is necessary and sufficient for the human to make the decision, and when the human must share the responsibilities for control with the machine.

However, there is another intriguing subset of this third category which will occur when we accept that the human may not always be the most competent decision maker, and when the correct perception of the state of the world may only reside with the machine member of the team. A system in which human users can override the machine partner compromises the goal of developing truly cooperative human-machine systems. A joint cognitive system implies a productive relationship between the knowledge of the machine and that of the human in which the different points of view are integrated in the decision process. Someday, we may consider the case when the human is no longer the sole supplier of the initiative, the direction, the integration, and the standards. We may accept that the safest and most efficient system is one that incorporates considerable duplication or interchangeability of functions among its human and non-human crew members and thus benefits from the strengths of both. However, I do not foresee acceptance of this concept within the life of the SEI program, and so I limit myself to developing the philosophy for the human-centered design of partially automated subsystems that fall into the third category described above.

The assumption that all critical decisions during the SEI missions will be left to the judgment of the human member of the team, has considerable significance to the designs of subsystems in the third category. Error-free operations by humans is impossible. Cicero said "It is in the nature of man to err". However restrictive is the crew-selection process and however much is invested in training and checking, there will still be residual human errors. Consequently, even though the human will be assigned responsibility for all the critical decisions, we must accept the inevitability of human error and we must design the system to minimize the consequences of these remaining errors. (Ref 7, 15) Furthermore, the system hardware must not make it difficult for the human to assume these responsibilities. There is no point in relying on the real or imagined virtues of human flexibility and innovation if the man-machine interface is so restrictive that the controller is unable to be either flexible or innovative in the actions which the system allows him to initiate. The objectives of a human-centered design should be to support humans to achieve the operational objectives for which they are responsible. The human role must be treated as central and the machine must be used to assist the human in achieving his goals rather than to supplant him. Consequently, the first question to be asked in a human-centered design philosophy is "In this situation, what is it that we expect the human to be able to do?", followed by the question "What information and control must he have in order to do it?"

Even with the imposition of the human-centered constraint on the design, thinking of humans and machines as working together as a total system is an appropriate orientation toward system design for CASE 3. Dr. Jane Malin at the NASA Johnson Space Center has called this *"making intelligent systems team players"*. (Ref 26, 27, 28) My colleague at Ames, Dr. Mary Connors, has used the term *"crew system"* to include all active, intelligent flight participants, both human and automated; and the term *"crew system dynamics"* to describe all activity of these members, both alone and in combination. (Ref 21) The Committee on Human Factors of the National Research Council (Ref 16) has said that *"A system is any identifiable set of mutually influential entities associated for the purpose of producing desired changes in the attribute state of objects."* I propose that we view the systems of CASE 3 in this context as being composed of teams of human and non-human entities, in contrast to prevalent concepts of design that consider only the non-human entities and exclude the human entities. (Ref 29) The mutual influences among the entities constitute interactions, and system effectiveness is concerned with optimizing these interactions, rather than the individual behaviors, except as there are behavioral limits on all entities. This approach recognizes that, just as in a team of human performers, proficiency of the individual entities does not assure proficient and effective team or system performance. (Ref 7,8)

Currently, the problem of the human-computer interaction is often considered to be merely one of interface design. In the case of the partially automated systems in CASE 3 that rely on interactive cooperation, this viewpoint is no longer appropriate. Interface design corresponds to playing with the language when the problem that interferes with communication of information and understanding is that humans come from a "culture" that is totally different from that of the non-human intelligence. Differences in the processes of problem solving and decision making are deeply rooted in the respective traditions and cultures of humans and machines. Machines do not sense data, process it, solve problems, make decisions, learn from experience, or take actions the way humans do. Machine logic is not the same as human logic. In fact, not everything that humans do is completely logical. It is easy to accept that a non-human intelligence cannot be expected to understand a human. It is equally true, even if not so obvious, that a human cannot be expected to understand a non-human intelligence. (Ref 30, 31) Without a doubt, improperly designed interfaces will interfere with understanding, but even the most elegantly designed interface will not assure understanding under all circumstances. One cannot simply build an automated system and then overlay it with interface features, and expect to achieve mutual understanding between the human and the machine. (Ref 25)

A well-executed interface design is a necessary, but not a sufficient, condition for cooperation. The objective of interface design is simply to put the data in the mode (i.e., visual, auditory, tactile, etc) and the format (i.e., alphanumeric, iconic, clock dials, thermometer tapes, color, font, size, location, etc) to maximize the likelihood that the human can translate the data displayed into information. (It is not information until it is perceived as such by the observer. The display designer cannot declare that his display is information, because the act of informing does not guarantee a state of being informed.) Interface design has little to do with ensuring that the information is necessary and sufficient for the human to understand the <u>state of the system</u>. (Ref 9, 17) Unless observers can effectively decode the representation to extract relevant information (as defined individualistically by the observer), the representation will fail to support the user. Most of the research on human-computer interface design is limited to studying the changes in the "language" that may be necessary for understanding, rather than on the determination of what is sufficient for understanding. As Marshall has stated it, there is a common perception that human factors specialists *"...should be brought in to sprinkle magic dust on the interface or workstation once it is largely developed"*. (Ref 32) The danger of focusing on things like icon shapes and colors or pull-down menus rather than the more fundamental issue of whether the appropriate information is being transferred is discussed by Woods and Eastman. (Ref 33)

The process by which a human translates his psychological representations of the system state, his goals, and his intentions into physical actions entails a good deal more than extracting information from his sensor inputs. To perform a particular task, the human selects and recognizes patterns representing the system state, integrates the inputs to all of his sensors, relates the integrated inputs to his preconceived representations, decides what further information he needs and acquires it, infers what this information implies, adds his own previous knowledge about the actual and potential states of the situation and his own value structure, biases, and emotions, predicts what will happen next, and considers actions to produce the desired state in order to arrive at the appropriate decisions. To interpret the outcome of his actions, the human must be able to perceive the resulting system state and relate those perceptions to his psychological representations. A problem will ensue if the non-human intelligence interferes with any part of this fundamental process. (Ref 32, 33, 34)

Examples of these problems are to be found in our experiences with current advisory systems. Many of the initial expert systems, that were called consultant or advisory systems, possessed very little capability for supporting cooperative interaction with human operators. (Ref 25) People learning to use advisory devices bring with them prior assumptions about the state of the world, and cause-effect and goal-action relations. They use these assumptions in trying to understand the instructions, in devising a plan of what to do, and then in trying to understand why the machine did not do what they had expected. Interference with understanding and, hence, collaboration result when the human and the advisory system do not have the same representations of the state of the world (or of each other or of the system that both are monitoring). People have difficulty accepting advice that appears to be inconsistent with their prior assumptions about the actual and potential states of the situation. (Ref 35) Current advisory systems usually use question-and-answer dialogs as the mechanism for achieving common understanding through explanation. It has been demonstrated in a variety of applications of advisory systems that these dialogs are not conducive to cooperative interaction because they must be structured to fit the machine's model of the world which may not coincide with that of its human partner. The human has no possibility of conveying to the machine his own perceptions of the state of the world which may be influenced by factors that have no meaning to the machine. For instance, it seems inevitable that experts will sometimes disagree and, yet, there has never been a provision for an expert user to register that he does not agree with what the system is doing, and to compare reasons for his disagreement with the rationale of the system. There is no possibility for the man and the machine to discover how much each knows or what each knows nothing about. Furthermore, if the human has an incorrect image of the machine's model of the world, he may not be able to fit correctly any conclusions of the machine into his image regardless of the degree of sophistication of explanations.

The problem is that, in the current state of advisory-system design, the machine and the human are not sharing information and perceptions about the state of the world in a manner that will enable the <u>system</u> to arrive at a single consensus decision, and take an agreed upon coordinated action. The solution to the problem of designing cooperative human-machine systems is not in better interface designs or better explanations. The problem and its solution reside elsewhere.

Cooperation is an information transfer problem which is inherently an interactive process. We will never achieve an interactive capability between human and non-human intelligence as long as we continue to design the machine without consideration of the perceptual and cognitive limitations and capabilities of the human. The power of a human-machine system resides in the system design that makes the most effective use of the complementary characteristics of all of its components. Therefore, we need a design philosophy based on a concept that forces us to think about men <u>and</u> machines working together in a partnership to perform a task. In this philosophy, the allocation of tasks between men and machines becomes a meaningless concept.

It is worth recalling some of the guidelines suggested by Wiener and Curry in their 1980 landmark paper titled "Flight Deck Automation: promises and problems" as they foresaw many of the issues that I am trying to address in this new design philosophy. (Ref 36) They pointed out, even then, that the question was *"not whether a function can be automated, but whether it should, due to the various human factor questions that are raised"*. They questioned the assumption that automation can eliminate error, pointed out failures in the interaction of humans with automation, and stated that *"the rapid pace of automation is outstripping one's ability to comprehend all the implications for crew performance"*. Their guideline statements noted, for example, that system performance of a task must be easily interpretable by the operator, and in a way the user wants it done. Their caution to designers to be aware of possible behavioral effects of automation is still valid a decade later, and this paper expands on those same concerns in developing a new approach to man-machine system design.

I propose that the coordinated activity when a team of individuals is required to perform a complex task is the appropriate model on which to base a design philosophy for human-machine collaboration. I suggest that we might structure such a philosophy on the bases of the relevant empirical work on human-to-human interaction during cooperative problem solving, and to relate the characteristics required of effective and valued human members of the team to the design requirements of the non-human member. The results of NASA's extensive research in group dynamics are particularly relevant at the higher levels of human-machine integration required for this design philosophy.

My colleagues at Ames have been studying the characteristics of teamwork among the members of the flight deck crew of commercial transports to develop models of effective crew functioning and to understand the sources of performance breakdowns. They have found that many performance failures were caused, not by lack of technical skills, but by problems in coordination among crew members. They have concluded that the foundation for achieving effective crew coordination resides within information transfer processes. Crew performance depends on the fundamental communication mechanisms by which crewmembers coordinate their activities, transmit and receive information, and solve problems. Communication variations are not only task related, they are also crew related. (Ref 37, 38) Successful communication is a collaborative effort that includes such esoteric behavioral qualities as coordination, compensatory behavior, mutual performance monitoring, exchange of feedback, and adaptation to varying situational demands. The proper exchange of information also depends on the skills that allow team members to predict and anticipate the actions of other team members, and can be influenced by socio-psychological factors. It is not a simple problem to understand the mechanisms that are important to successful communication among humans. It is significantly more difficult to relate this understanding to the design features necessary and sufficient to ensure successful communication between humans and machines, and, yet, that is what I believe is needed in the new philosophy of design.

Billings' first guideline to human-centered design for aircraft automation states that human-centered automation should possess the following attributes in "proper measure": (Ref 15)

1. Accountable; i.e., must inform the pilot of its actions and explain them on request.
2. Subordinate; i.e., should never assume command, except in pre-defined situations in which it can be countermanded easily.
3. Predictable; i.e., operations must be, and appear to be, predictable to the pilot, but, at the same time, must be
4. Adaptable; i.e., configurable within a wide range of pilot preferences.
5. Comprehensible; i.e., intelligible, and simple to understand, but,also

6. Flexible; i.e., should enable a range of control and management options from direct manual to autonomous.
7. Dependable; i.e., do what it is ordered to do, never do what it is not ordered to do, and never make the situation worse, but, as perfection is impossible, it must also be
8. Informative; i.e., keep the pilot well informed about what is going on.
9. Error resistant; i.e., keep the pilots from making errors, but, at the same time, recognizing that this is not always possible, it must also be
10. Error tolerant; i.e., detect and mitigate the effects of pilot errors.

All of these "attributes" can be related to the characteristics that the Ames researchers have found to be important to effective human-to-human communication.

In this design philosophy, both the machine and the human are viewed as information-processing systems capable of independent, complex behavior. In order to ensure reliable coordination, we will need to understand the processes of cognition of both entities and the processes of information transfer needed to achieve compatibility. (Ref 5) For the human members of the crew, the solution to the problem of ensuring effective coordination and communication is a matter of proper selection, training, and organizational management; for the non-human member, it becomes a matter of proper design.

VI. A POSSIBLE APPROACH

Simulation has become an important tool for investigating the behavior of complex systems during conceptual and preliminary design. However, the analysis of system performance through simulation requires efficient and effective representations of significant parameters of interaction among its entities. The designer/analyst must have the ability to examine and manipulate component models. Therefore, to make effective use of simulation during preliminary design of the SEI human-machine systems, we need, in addition to the usual models of the equipments and environments, a model of the human activities, a model of the tasks to be accomplished and of the role that the human is expected to play in accomplishing those tasks, and a model of the human capabilities, limitations, and needs to play that role. (Ref 5)

I am not suggesting that we will realize a true computational emulation of the human brain in the near future. We are only at the most elemental levels of understanding the relationships between the human mind and behaviors and the biological structures and electrochemical processes of the brain. We are far from implementing the neurophysiological mechanisms in symbolic processors or connectionist networks to emulate the human cognitive and perceptual system.

For the present, however, we can settle for a good deal less. In order to be able to address human factors issues during the conceptual design stages of missions and systems, we need engineering human performance models.with which we can examine, at least, the first-order effects of the complementary contributions of human and machine to a system. Professor Gerlach already addressed this need in 1986 in his biomorphic model of the physiological and psychological processes in a human in a single-display, single-axis control situation. (Ref 39)

Even though we cannot emulate the human brain, there is considerable promise for an adequate model to simulate the way in which a human might or could act in a particular situation. For instance, we have recently seen some great improvements in anthropometric modeling that promise to meet adequately one of the requirements for model-based human engineering. Today, we have extremely elegant anthropometric models of easily created, realistic, and physically quantifiable human-figure motion via an interactive computer graphics system. The designer is able to select human figures of different sizes that include the 5th, 50th, and 95th percentile male and female, based on NASA astronaut demographics. These figures can be placed within a three-dimensional object environment that can be created and stored. Joint limitations have been installed to eliminate unreasonable movements, and kinematic and inverse kinematic controls are applied so that goals and constraints may be used to position and orient the figure with external/internal forces and torques applied to produce motion. Key poses can be stored and interpolated for animation, allowing environmental limitations to be detected as a function of human size and movement characteristics. Recent developments include a new 17-segment vertebral column for very realistic torso movements, preliminary collision detection/avoidance mechanisms, and new figure definitions based on detailed stereo-scanned images from several somatotypes in each gender. In addition, by attaching the "view" of the environment to the mannequin's eye, the program displays a perspective corresponding to what the mannequin would "see" while moving in the environment, providing the first step toward further analysis and conclusions about object occlusion and visibility. We are currently using this model in the Man-machine Integration Design and Analysis System (MIDAS) being developed at Ames in collaboration with the US Army. (Ref 40, 41) Our colleagues at the NASA Johnson Space Center are accumulating the data to extend the strength and motion characteristics of these models for use in micro-gravity simulations. With models like these we can begin to address some of the ergonomic issues of design.

More recently, we have begun developing computational methods for describing and analyzing cognitive tasks comparable with the methods we have for analyzing physical tasks. Considerable progress is being made in the new field of cognitive science where mechanistic models of humans performing complex perceptual, cognitive, and motor tasks are under development that may allow us to go beyond the descriptive approach of traditional experimental psychology. Current research at NASA Ames on computational modelling of human perception and cognition represent some encouraging attempts to describe how humans accomplish various mental tasks.

The Cognition Simulation System (CSS) being developed by my colleagues at Ames is just one representative study. (Ref 42) The CSS is a software system intended to aid researchers in designing and evaluating models of human cognition by providing an interactive, graphics-based simulation environment. CSS is a discrete-event simulation system specialized for simulating distributed, partly parallel, partly serial processing systems, like those typically hypothesized to underlie human information processing. CSS can be used more generally to model any distributed system, and incorporates some of the power of production systems. CSS has been used to date to model the role of human attention in visual information processing, to model the delays imposed by doing two tasks at once, and to model the flow of information during preparation for launch between the NASA Test Director at the Kennedy Space Center and his various external information sources and equipment.

One important focus of interest at our Aerospace Human Factors Research Division is the integration of these CSS models into the MIDAS architecture. The Symbolic Operator

Model (an element of the MIDAS) models human perceptual processes, cognitive processes, and response/effector processes using an integrated object-oriented architecture. This model also provides a limited description of human neuromotor response and verbal communication protocols. MIDAS includes the computational structures and utilities required to support the modeling environment and knowledge-base through which these components interact, including an updateable world representation, activity/procedural representation, and rules and decision methods which guide operator behavior in selection among several contingent procedural paths and are responsive to the current mission context.

Construction of useful, integrated, mechanistic, engineering models of human performance now seems possible. However, these studies have, so far, been limited to modeling single individuals. We are moving toward explicit attacks on the problem of how individual cognition interacts with perceptual, physiological, and group factors. We need now to begin to consider communications between such models and to factor into these new models those elements that we have found important to transfer of information and coordination. The agent architecture of the computational models we have developed not only enables us to modify any of the components easily, but also is particularly suited to studying an intermix of human and non-human agents.

Validation of our computational models is essential, but extremely difficult. A fundamental problem of all Human Factors research is that the tools and theories that have been developed in highly simplified and controlled laboratory environments are of little assistance in understanding human behavior in the complex and varied environment of aerospace operations.

Another major difficulty in trying to build predictive models of human behavior is the fact that behavior is often influenced by knowledge and emotions of which the actor is totally unaware. Perceptual-cognitive functions such as discriminative response to stimulation, perception, memory, information processing, complex cognitive activity devoted to stimuli that are themselves outside of awareness, and the higher-order mental processes involved in judgment or problem-solving can all take place outside of phenomenal awareness and can affect action. Realistically, we may never be able to find reliable, validated, predictive models of systems in which human beings participate except in limited domains.

Nevertheless, with the continued development and validation of these models, we expect to use them in simulations to develop guidelines for designs of missions, operations, and procedures, as well as automated systems.

VII. CONCLUSIONS

One day, the intelligence of a computer may rival that of the human brain. One day, we may learn how to couple human brains and computing machines in truly cooperative partnerships. For now, however, we must continue to rely on human intelligence, judgment, flexibility, creativity, and imagination in dealing with unexpected events, while complementing these with machine capabilities for logic, speed, persistence, consistency, and exactitude.

In order to achieve the objectives of human exploration of space envisioned in the SEI program, we will need to learn how to integrate humans with machines to an extent far beyond our current understandings. Our experience with automation in aviation convinces us that current design philosophies based, largely, on allocation of functions and human adaptability will not enable us to design the machines required to perform the SEI missions with assurance of safe and reliable human interactions. We need to adopt a philosophy of design that views the total system composed of human and non-human entities. We need to be able to address human factors issues during the conceptual design stages of missions and systems, and, for this, we will rely on simulations. Consequently, we need computational human performance models.with which we can examine the effects of the complementary contributions of the human and machine components to total system performance.

We have only just begun to develop the models we need. Much research remains to understand the perceptual and cognitive functions, the informational requirements, and the mechanisms of communication adequately to model human interaction with non-human intelligence. Research is needed that transcends the boundaries between the physical, psychological, and social sciences. We need a full-spectrum, coordinated research program calling for expertise in psychophysics, perception, cognition, physiology, behavior, and group factors; utilizing a variety of approaches including analyses, laboratory experiments, human-performance modeling, partial-task and full-mission simulators, testbeds, field and analog-environment studies, MIDAS-style integrated human-engineering modeling and simulation, and space-flight tests..

I am going to conclude with a few recommendations for required research, but it is important to remember that research focused on any of these problem areas should not isolate itself from the system and the context within which it is embedded. Also, we cannot investigate the way in which humans relate to non-human intelligence without adequately representing the social environment within which the task is being carried out. The following recommendations are not significantly different from those made by the Committee on Human Factors of the National Research Council already in 1987. Ref 43

RECOMMENDATION 1: Design and support an aggressive program leading to the understanding of human crew functioning and interactions, cooperative problem solving, cooperative decision making, and productivity under stressful conditions, including continual and intermittent exposures to multiple physiological and psychological stressors.

RECOMMENDATION 2: Design and support an aggressive program leading to the understanding of the nature of teamwork skills and how they develop, particularly in teams composed of different cultural backgrounds. An understanding of "teamwork" is not only important to developing the proper techniques for selection, training, and organization of human crews, but is also essential to development of design guidelines for complex, automated (and, possibly, learning) systems with which humans will need to cooperate.

RECOMMENDATION 3: Design and support an aggressive research program leading to the eventual development of human-computer systems for cooperative control, information, and management . This is the most difficult of the technological goals related to cognitive science associated with the SEI missions, and requires development of design principles based on using model-based theories of cognition.

Our current situation cries out for cooperative research as there does not exist in any one nation sufficient resources in either expertise or money to solve these problems in a reasonable time. I feel a sense of urgency, because while we are still struggling with the science to understand the problems, the engineering community is spending a great deal of money designing the solutions.

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