

HUMAN FACTORS IN AUTOMATED AND  
ROBOTIC SPACE SYSTEMS

PROCEEDINGS OF A SYMPOSIUM:

PART II

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DECISION MAKING -- AIDED AND UNAIDED

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Baruch Fischhoff

Eugene Research Institute

Eugene, Oregon

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## INTRODUCTION

Decision making is part of most human activities, including the design, operation, and monitoring of space station missions. Decision making arises whenever people must choose between alternative courses of action. It includes both global decisions, such as choosing a station's basic configuration, and local decisions, such as choosing the best way to overcome a minor problem in executing an onboard experiment. Decision making becomes interesting and difficult when the choice is non-trivial, either because decision makers are unsure what outcomes the different courses of action will bring or because they are unsure what outcomes they want (e.g., what tradeoff to make between cost and reliability).

Much of science and engineering is devoted to facilitating such decision making, where possible even eliminating the need for it. A sign of good engineering management is that there be no uncertainty about the objectives of a project. A sign of advanced science is that there are proven solutions to many problems, showing how to choose actions whose outcomes are certain to achieve the chosen objectives. Where the science is less advanced, the hope is to routinize at least part of the decision-making process. For example, the techniques of cost-benefit analysis may make it possible to predict the economic consequences of a proposed mission with great confidence, even if those techniques cannot predict the mission's risks to lives and property or show how those risks should be weighed against its economic costs and benefits (Bentkover et al., 1985;

Fischhoff et al., 1981). Or, current engineering knowledge may allow automation of at least those decisions where electronic sensors or human operators can be trusted to provide accurate initial conditions. Indeed, space travel would be impossible without extensive computer-controlled decision making for problems involving great computational complexity or time pressure (e.g., during launch).

An overriding goal of space science (and other applied sciences) is to expand both the range of problems having known solutions and the technological capability for deriving and activating those solutions without human intervention. In this pursuit, it is aided by concurrent efforts in other fields. Among them is cognitive science (broadly defined), whose practitioners are attempting to diversify the kinds of problems that can be represented and solved by computer.<sup>1</sup>

Yet, however far these developments progress, there will always be some decisions that are left entirely to human judgment and some elements of judgment in even the most automated decisions. For example, there is no formula for unambiguously determining which basic design configuration will prove best in all anticipated circumstances (much less unanticipated ones). Analogously, there is no proven way to select the best personnel for all possible tasks. When problems arise, during either planning or operation, judgment is typically needed to recognize that something is wrong and to diagnose what that something is. When alarms go off, judgment is needed to

decide whether to trust them or the system that they mistrust. When no alarms go off, supervisory judgment is needed to decide whether things are, in fact, all right. However thorough training may be, each operator must continually worry about whether others have understood their (possibly ambiguous) situations correctly, and followed the appropriate instructions. When solutions are programmed, operators must wonder how good the programming is. When solutions are created, engineers must guess at how materials (and people) will perform in novel circumstances. Although these guesses can be aided and disciplined by scientific theories and engineering models, there is always some element of judgment in choosing and adapting those models, compounding the uncertainty due to gaps in the underlying science. Any change in one part of a system creates uncertainties regarding its effects on other system components. In all of these cases, wherever knowledge ends, judgment begins, even if it is the judgment of highly trained and motivated individuals (Fischhoff, 1987; McCormick, 1981; Perrow, 1984).

Understanding how good these judgments are is essential to knowing how much confidence to place in them and in the systems that depend on them. Understanding how those judgments are produced is essential to improving them, whether through training or judgmental aids. Such understanding is the goal of a loosely bounded interdisciplinary field known as behavioral decision theory. The "behavioral" is meant to distinguish it from the study of decision making in mainstream American economics, which rests on the metatheoretical assumption that people always optimize when they make

decisions, in the sense of identifying the best possible course of action. Although plausible in some circumstances and essential for the invocation of economics' sophisticated mathematical tools, the assumption of optimization severely constrains the kinds of behavior that can be observed. It also leaves economics with the limited (if difficult) goal of discerning what desires people have succeeded in optimizing in their decisions. Behavioral decision theory is concerned with the conditions conducive to optimizing, the kinds of behavior that come in its stead, and the steps that can be taken to improve people's performance (Fischhoff et al., 1981; Kahneman et al., 1981; National Research Council, 1986; Schoemaker, 1983; von Winterfeldt and Edwards, 1986).

Research in this tradition draws on a variety of fields, including psychology, operations research, management science, philosophy, political science, and (some) economics. As it has relatively little institutional structure, it might be best thought of as the conjunction of investigators with several shared assumptions. One is the concurrent pursuit of basic and applied knowledge, believing that they are mutually beneficial. A second is the willingness to take results from any field, if they seem useful. A third is interest in using the latest technology to advance and exploit the research. These are also the assumptions underlying this chapter, which attempts to identify the most promising and important research directions for aiding space station development. Because of the space station's role as a pioneer of advanced technology, such

research, like the station itself, would have implications for a wide range of other applications.

The results of research in behavioral decision theory have shown a mixture of strengths and weaknesses in people's attempts to make decisions in complex and uncertain environments. These intuitive psychological processes pose constraints on the decision-making tasks that can be imposed on people and, hence, on the quality of the performance that can be expected from them. These processes also offer opportunities for decision aiding, by suggesting the kinds of help that people need and can accept. The following section provides a brief overview of this literature and points of access to it, couched in quite general terms. The next section considers some of the special features of decision-making in space station design and operation. The following three sections discuss the intellectual skills demanded by those features and the kinds of research and development needed to design and augment them. These properties are the needs: (a) to create an explicit model of the space station's operation, to be shared by those involved with it, as a basis for coordinating their distributed decision making, (b) to deal with imperfect systems, capable of responding in unpredictable ways, and (c) to manage novel situations. A concluding section discusses institutional issues in managing (and exploiting) such research, related efforts (or needs) in other domains, and the philosophy of science underlying this analysis.

## SPACE STATION DECISIONS AND THEIR FACILITATION

Most prescriptive schemes for deliberative decision making (Behn and Vaupel, 1982; Raiffa, 1968; von Winterfeldt and Edwards, 1986), showing how it should be done, call for performing something like the following four steps:

- a. Identify all possible courses of action (including, perhaps, inaction).
- b. Evaluate the attractiveness (or aversiveness) of the consequences that might arise if each course of action is adopted.
- c. Assess the likelihood of each consequence occurring (should each action be taken).
- d. Integrate all these considerations, using a defensible (i.e., rational) decision rule to select the best (i.e., optimal) action.

From this perspective, decisions are evaluated according to how well they take advantage of what was known at the time that they were made, vis-a-vis achieving the decision maker's objectives. They are not evaluated according to the desirability of the consequences that followed. Some decisions involve only undesirable options, while the

uncertainty surrounding other decisions means that bad things will happen to some good choices.

The following is a partial list of decisions that might arise in the course of designing and operating a space station. Each offers a set of action alternatives. Each involves a set of consequences whose relative importance must be weighed. Each is surrounded by various uncertainties whose resolution would facilitate identifying the optimal course of action:

Deciding whether to override an automated system (or deciding what its current state actually is, given a set of indicators);

Deciding in advance how to respond to a potential emergency;

Deciding where to look for some vital information in a computerized database;

Deciding whether to proceed with an extravehicular operation when some noncritical, but desirable safety function is inoperative;

Deciding whether to replace a crew member having a transient medical problem (either when formulating general operational rules or when applying them at the time of a launch);

Deciding where to put critical pieces of equipment;

Deciding how to prioritize the projects of different clients,  
both in planning and in executing missions;

Deciding where to look first for the sources of apparent  
problems;

Deciding which ground crew actions deserve an extra double check;

Deciding whether the flight crew is up to an additional period in  
orbit;

Deciding what to do next in a novel manipulation task;

Deciding on the range of possible values for a parameter needed  
by a risk analysis of system reliability;

Deciding just how much safety will be increased by a design  
change, relying on a risk analysis to project its system-wide  
ramifications;

Deciding what to report to outsiders (e.g., journalists,  
politicians, providers of commercial payloads) about complex  
technical situations that they are ill-prepared to understand.

These decisions vary in many ways: who is making them, how much  
time is available to make them, what possibilities there are for

recovering from mistakes, how great are the consequences of success and failure, what computational algorithms exist for deciding what to do, how bounded is the set of alternative actions, and where do the greatest uncertainties lie, in evaluating the importance of the consequences or in evaluating the possibilities for achieving them. What these decisions have in common is that some element of unaided human judgment is needed before an action is consummated, even if it is only the decision to allow an automated process to continue unmolested. Judgment is needed, in part, because there is some element of uniqueness in each decision, so that it cannot be resolved simply by the identification of a procedural rule (or set of rules) that has proven itself superior in past applications. The search for rules might be considered an exercise in problem solving. By contrast, decision making involves the intellectual integration of diverse considerations, applying a general purpose integrative rule intended to deal with novel situations and "get it right the first time." In "interesting" cases, decision making is complicated by uncertain facts (Wise, 1986), so that one cannot be assured of the outcome (and of which choice is superior), and of conflicting consequences, so that no choice is superior in all respects (and some tradeoffs must be made)<sup>2</sup>.

As mentioned, the hope of behavioral decision theory is to discern basic psychological processes likely to recur wherever a particular kind of judgment is required. One hopes, for example, that people use their minds in somewhat similar ways when determining the probability that they know where a piece of information is

located in a database and when determining the probability that they can tell when an anomalous meter reading represents a false alarm. If so, then similar treatments might facilitate performance in both settings<sup>3</sup> (Fischhoff and MacGregor, 1986; Murphy and Winkler, 1984).

The need to make decisions in the face of incomplete knowledge is part of the human condition. It becomes a human factors problem (the topic of this volume) either when the decisions involve the design and operation of machines (broadly defined) or when machines are intended to aid decisions. Decisions about machines might be aided by collecting historical data regarding their performance, by having them provide diagnostic information about their current trustworthiness, by providing operators with training in how to evaluate trustworthiness (and how to convert those evaluations into action), and by showing how to apply general organizational philosophies (e.g., safety first) to specific operating situations. Decision aiding by machines might be improved by enhancing the display of information that operators understand most poorly, by formatting these displays in ways compatible with users' natural ways of thinking, by clarifying the rationale for the machine's recommendations (e.g., its assumed tradeoffs, its decision rule, its treatment of uncertainty), and by describing the definitiveness of its recommendations. A better understanding of how people intuitively make decisions would facilitate attaining these objectives, as well as developing training procedures to help people make judgments and decisions wherever they arise. Just thinking

about decision making as a general phenomenon might increase the motivation and opportunities for acquiring these skills.

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DESCRIPTIONS OF DECISION MAKING

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One way of reading the empirical literature on intuitive processes of judgment and decision making is as a litany of problems. At each of the four stages of decision making given above, investigators have identified seemingly robust and deleterious biases: When people generate action options, they often neglect alternatives that should be obvious and, moreover, are insensitive to the magnitude of their neglect. As a result, options that should command attention are out of mind when they are out of sight, leaving people with the impression that they have analyzed problems more thoroughly than is actually the case (Fischhoff et al., 1978; Pitz et al., 1980). Those options that are noted are often defined quite vaguely, making it difficult to evaluate them precisely, communicate them to others, follow them if they are adopted, or tell when circumstances have changed enough to justify rethinking the decision (Bentkover et al., 1985; Fischhoff et al., 1984; Furby and Fischhoff, 1987; Samet, 1975). Imprecision also makes it difficult to evaluate decisions in the light of subsequent experience, insofar as it is hard to reconstruct exactly what one was trying to do and why. That reconstruction is further complicated by hindsight bias, the tendency to exaggerate in hindsight what one knew in foresight (Fischhoff, 1975). The feeling that one knew all along what was going to happen can lead one to be unduly harsh on past decisions (if it was

relatively obvious what was going to happen, then failure to select the best option must mean incompetence) and to be unduly optimistic about future decisions (by encouraging the feeling that things are generally well understood, even if they are not working out so well).

Even though evaluating the relative importance of potential consequences might seem to be the easiest of the four stages of decision making, a growing literature suggests that people are often uncertain about their own values. As a result, the values that they express can be unstable and unduly sensitive to seemingly irrelevant features of how evaluation questions are posed. For example, (a) the relative attractiveness of two gambles may depend on whether people are asked how attractive each is or how much they would pay to play it (Grether and Plott, 1979; Slovic and Lichtenstein, 1983); (b) an insurance policy may become much less attractive when its "premium" is described as a "sure loss" (Hershey et al., 1982); (c) a risky venture may seem much more attractive when described in terms of the lives that will be saved by it, rather than in terms of the lives that will be lost (Kahneman and Tversky, 1979; Tversky and Kahneman, 1981). Thus, uncertainty about values can pose as serious a problem to effective decision making as can uncertainty about facts.

Although people are often willing to acknowledge uncertainty about what will happen, they are not always well equipped to deal with it, in the sense of assessing the likelihood of future events (in the third stage of decision making). A rough summary of the voluminous literature on this topic is that people are quite good at

tracking repetitive aspects of their environment, but not as good at combining those observations with inferences about what they have not seen (Hasher and Zacks, 1984; Kahneman et al., 1982; Peterson and Beach, 1967). Thus, they might be able to tell how frequently they have seen or heard about deaths from a particular cause, but not be able to assess how representative their experience has been--leading them to overestimate risks to which they have been overexposed (Combs and Slovic, 1979; Tversky and Kahneman, 1973). They can tell what usually happens in a particular situation and recognize how a specific instance is special, yet have difficulty integrating these two (uncertain) facts--with the most common bias being to focus on the specific information and ignore experience (or "base rates") (Bar Hillel, 1980). They can tell how similar a specific instance is to a prototypical case, yet not how important similarity is for making predictions--usually relying on it too much (Bar Hillel, 1984; Kahneman and Tversky, 1972). They can tell how many times they have seen an effect follow a potential cause, yet not infer what that says about causality--often perceiving relations where none exist (Beyth-Marom, 1982; Einhorn and Hogarth, 1978; Shaklee and Tucker, 1980). They have a rough feeling for when they know more and when they know less, but not enough sensitivity to avoid a commonly observed tendency toward overconfidence (Fischhoff, 1982; Wallsten and Budescu, 1983).

According to decision theory, the final stage of decision making should involve implementation of an expectation rule, whereby an option is evaluated according to the attractiveness of its possible

consequences, weighted by their probability of occurrence. Since it has become acceptable to question the descriptive validity of this rule, much research has looked at how well it predicts behavior (Dawes, 1979; Feather, 1982; Fischhoff et al., 1981; Kahneman et al., 1982; National Research Council, 1986; Schoemaker, 1983). A rough summary of this work would be that: (a) the expectation rule often predicts people's choices fairly well--if one knows how they evaluate the probability and attractiveness of consequences; (b) with enough ingenuity, one can usually find some set of beliefs (regarding the consequences) for which the rule would dictate choosing the option that was selected--meaning that it is hard to prove that the rule was not used; (c) expectation rules can often predict the outcome of decision-making processes even when they do not at all reflect the thought processes involved--so that predicting behavior is not sufficient for understanding or aiding it; (d) those processes seem to rely on rules with quite different logics, many of which appear to be attempts to avoid making hard choices by finding some way to view the decision as an easy choice--for example, by disregarding consequences on which the otherwise-best option rates poorly (Janis and Mann, 1977; Montgomery, 1983; Payne, 1982; Simon, 1957).

The significance of these results from experimental studies depends upon how well they represent behavior outside the lab, how much insight they provide into improving decision making, and how adversely the problems that they reveal affect the optimality of decisions. As might be expected, there is no simple answer to any of

these questions. Life poses a variety of decisions, some of which are sensitive to even modest imprecision in their formulation or in the estimation of their parameters, some of which yield an optimal choice with almost any sensible procedure, and some of which can tolerate occasional inaccuracies, but not recurrent problems, such as persistently exaggerating how much one knows (Henrion, 1980; Krzysztofowicz, 1983; McCormick, 1981; von Winterfeldt and Edwards, 1982). Placing decisions within a group or organizational context may ameliorate or exacerbate problems, depending on how carefully members scrutinize one another's decisions, how independent are the perspectives that they bring to that scrutiny, and whether that social context has an incentive structure that rewards effective decision making (as opposed to rewarding those who posture or routinely affirm common misconceptions) (Davis, 1982; Lanir, 1982; Myers and Lamm, 1976).

The robustness of laboratory results is an empirical question. Where evidence is available, it generally suggests that these judgmental problems are more than experimental artifacts, which can be removed by such "routine" measures as encouraging people to work harder, raising the stakes contingent on their performance, clarifying instructions, varying the subject matter of the tasks used in experiments, or using better educated subjects. There are many fewer studies than one would like regarding the judgmental performance of experts working in their own areas of expertise. What studies there are suggest some reason for concern, indicating that experts think like everyone else, unless they have had the conditions

needed to acquire judgment as a learned skill (e.g., prompt, unambiguous feedback) (Fischhoff, 1982; Henrion and Fischhoff, 1986; Murphy and Winkler, 1984).

The evidentiary record is also incomplete with regard to the practical usefulness of this research. The identification of common problems points to places where human judgment should be supplanted or aided. The acceptance of decision aids (and aides) has, however, been somewhat limited (Brown, 1970; Fischhoff, 1980; Henrion and Morgan, 1985; von Winterfeldt and Edwards, 1986). One inherent obstacle is presenting users with advice derived by inferential processes different than their natural ones, leaving uncertainty about how far that advice is to be trusted and whose problem it really is solving. Developing (and testing) decision aids that took seriously the empirical results of behavioral decision theory would be a useful research project. With regard to situations where decision aids are unavailable, there is some evidence that judgment can be improved by training procedures that recognize the strengths and weaknesses of people's intuitive thought processes (Kahneman et al., 1982; Nisbett et al., 1983). Here, too, further research is needed.

#### THE PSYCHOLOGICAL REALITY OF SPACE STATION DECISIONS

The recurrent demand for similar intellectual skills in diverse decisions means that any research into decision-making processes could, in principle, provide some benefit to the space station

program. However, there are some conditions that are particularly important in the space station environment and, indeed, might rarely occur in less complex and technologically saturated ones. The challenges posed by such conditions would seem to be suitable and important foci for NASA-supported research. Three such conditions are described in the remainder of this section. Each subsequent section considers research issues pertinent to one of these conditions. In each case, significant progress appears possible, but would appear to demand the sort of sustained programmatic effort that NASA has historically been capable of mustering.

Condition 1: The need to create a widely shared model of the space station and its support systems. The technical knowledge needed to manage the space program is widely distributed over diverse locations on earth and in space, in different centers on earth, and across different people within each earth and space center. As a result, there are prodigious technical problems involved in ensuring compatibility, consistency, and concurrency among the computerized databases upon which these scattered individuals rely. Even if these problems of information transmission can be resolved, there is still no guarantee that the diverse individuals at the different nodes in the system will be aware of the information available to them, nor comprehend its meaning for their tasks, nor be alert to all changes that might affect their work. Even with a static database, there may be problems of understanding when the individuals have very different kinds of expertise, such that their contributions to the database cannot be readily understood (or evaluated) by one another.

The management of such systems requires the creation of some sort of system-wide model within which individuals can pool their knowledge and from which they can draw needed information. That model may be a loosely organized database, with perhaps a routing system for bringing certain information to the attention of certain people (attempting to strike a balance between telling them too much and too little). Or, it may be an explicit coordinated model, such as those used in design processes guided by procedures like probabilistic risk analysis (McCormick, 1981; U.S. Nuclear Regulatory Commission, 1983). These models assign new information into an integrated picture of the physical system, possibly allowing computational predictions of system performance, which can be redone whenever the state of the system (or the theoretical understanding of its operation) changes. Shared models with such computational abilities can be used to simulate the system, for the sake of comparing the effects of design changes, training operators for emergencies, and troubleshooting (by seeing what changes in the system could have produced the observed aberrations). Such models are useful, if not essential, for achieving NASA's goal of allowing "crews to intervene at extremely low levels of every subsystem to repair failures and take advantage of discoveries" (NASA, 1986).

Less ambitious models include spreadsheets, status displays, even simple engineering drawings, pooling information from varied human and machine sources (although, ultimately, even machine-sourced information represents some humans' decisions regarding what

information should and can be summarized, transmitted, and displayed). All such models are based around a somewhat artificial modeling "language" which is capable of representing certain aspects of complex systems. Using them effectively requires "fluency" in the modeling languages and an understanding of their limits. Thus, for example, decision analysis (Behn and Vaupel, 1982; Raiffa, 1968; von Winterfeldt and Edwards, 1986) can offer insight into most decision-making problems, if decision makers can describe their situations in terms of options, consequences, tradeoffs, and probabilities--and if they can recognize how the problem described in the model differs from their actual problem. Probabilistic risk analyses can aid regulators and designers to understand the reliability of nuclear power plants by pooling the knowledge of diverse groups of engineers and operators--as long as everyone remembers that such models cannot capture phenomena such as the "intellectual common mode failure" that arises when operators misunderstand an emergency situation in the same way.

The creation, sharing, interpretation, and maintenance of such models are vital to those organizations that rely on them. The unique features of such models in the context of NASA's missions are their size and complexity, their diversity (in terms of the kinds of expertise that must be pooled), and their formality. That formality comes not only from the technical nature of much of the information but also from the need for efficient telecommunications among NASA's distributed centers. Formality complicates the cognitive task of communication, by eliminating the informal cues that people rely upon

to understand one another and one another's work. It may, however, simplify the cognitive study of such communication by rendering a high portion of significant behavior readily observable. It may also simplify the cognitive engineering of more effective model building and sharing, insofar as better methods can be permanently and routinely incorporated in the appropriate protocols. Research that might produce such methods is discussed below.

Condition 2: The need to make decisions with imperfect systems.

Decisions involving uncertainty are gambles. Although it is an uncomfortable admission where human lives are at stake, many critical decisions in space travel are gambles. The uncertainties in them come from the limits of scientific knowledge regarding exactly how various elements of a mission will perform, from the limits of engineering knowledge regarding how different system elements will interact, from the limits in the technical capacity for modeling complex systems, and from the unpredictability of human operators (who are capable of fouling and saving situations in novel ways). Indeed, despite NASA's deep commitment to planning and training, the nature of its mission demands that some level of uncertainty be maintained. It is expected to extend the limits of what people and machines can do. Performance at those limits cannot be tested fully in theoretical analyses and simulation exercises.

In order to gamble well, one needs both the best possible predictions regarding a system's performance and a clear appraisal of the limits of those predictions. Such an assessment of residual

uncertainty is needed in order to guide the collection of additional information, in order to guide preparation for surprises, and, most important of all, to guide the decision as to whether a mission is safe enough to proceed (considering NASA's overall safety philosophy). Using information wisely requires an understanding of just how good it is.

Because gambling is so distasteful, there is constant activity to collect (and produce) additional knowledge, either to perfect the system or to clarify its imperfections. As a result, the state of knowledge and the state of the system will be in constant flux, even without the continual changes of state associated with its ongoing operations (e.g., testing, training, wear). Somehow, this new information must be collated and disseminated, so that those concerned with the system know what is happening and know how much one another knows. In this way, dealing with uncertainty is related to dealing with a shared model.

For operators, this residual uncertainty creates the constant possibility of having to override the system, in order to rescue it from some unanticipated circumstance or response. That override might involve anything from a mild course correction to a fundamental intervention signalling deep distrust of a system that seems on the verge of disaster. As the physical stakes riding on the decision increase, so do the social stakes (in the sense of the responsibility being taken for system operation and the implicit challenge to system designers). Thus, operators, as well as designers and managers, must

be able to assess the system's trustworthiness and to translate that assessment into an appropriate decision.

The variety of individuals with knowledge that could, conceivably, prompt override decisions means that coping with uncertainty is an intellectual skill that needs to be cultivated and facilitated throughout the organization. It also means that the system's overall management philosophy must recognize and direct that skill. For example, a general instruction to "avoid all errors" implies that time and price are unimportant. Where this is not the case, personnel are left adrift, forced to make tradeoffs without explicit guidance. Such an official belief in the possibility of fault-free design may also discourage the treatment of those faults that do remain. Many failsafe systems "work" only because the people in them have learned, by trial and error, to diagnose and respond to problems that are not supposed to happen. Because the existence of such unofficial intelligence has no place in the official design of the system, it may have to be hidden, may be unable to get needed resources (e.g., for record keeping or realistic exercises), and may be destroyed by any change in the system that invalidates operators' understanding of its intricacies. From this perspective, where perfection is impossible it may be advisable to abandon near-perfection as a goal as well, so as to ensure that there are enough problems for people to learn how to cope with them. Moreover, steps toward perfection should be very large before they could justify disrupting accustomed relationships. That is, technological instability can be a threat to system operation.

Condition 3: The need to make novel decisions, in non-routine situations. With nearly perfect systems, rare problems are always somewhat novel. Even when they have been anticipated and incorporated in contingency plans, there is always some uncertainty about whether the problems that arise can be identified with the comparable problems described in the plans. Where the plans can be retrieved, there is still some uncertainty about whether they will seem like the right thing to do once the contingency is confronted "in the flesh." The retrieval of plans is an exercise in pattern matching. However, it also involves a series of decisions regarding whether a contingency has arisen, which plan is meant to fit the current situation, and whether that plan is to be trusted.

Yet other decision problems will be entirely novel and unanticipated. Such situations might be considered the purest form of decision making, clearly calling for the integration of diverse pieces of information in an effort to identify the right course of action, often having to get it right the first time. Where time constraints are great, such decision making may involve just the raw exercise of intuitive thought processes. Raw intuition may also be the primary ingredient for more leisurely decisions, when there is no accepted structure for decision making. That may happen, for example, when problems fall at the intersection of several jurisdictions or when they require tradeoffs regarding which the organization lacks policy.

In such situations, decision making may be seen as involving several kinds of "research." These include understanding the interactions among subsystems previously thought to be relatively independent, discerning how the organization's underlying safety philosophy applies to a particular novel case, generating action options to evaluate, and ferreting shared misconceptions.

When there is an algorithmic procedure for deciding what to do, the novelty of a decision may lie in having to deal with a unique state of the physical system. Understanding that state requires more than the usual troubleshooting (i.e. diagnosing which of a known set of problems has produced the observed symptoms). Rather than that sort of (sophisticated) pattern matching, unique states require the equivalent of on-line research. That research may involve short-term engineering analysis, using whatever aspects of the overall design model can be accessed within the time constraints. When formal models are inaccessible, then the analysis must be performed within the "mental models" of the decision makers and their aides. In either case, judgment is needed to choose the information-gathering procedures with the highest "yield," in terms of hypothesis testing.

In addition to the cognitive difficulties of making unique decisions, there may also be institutional difficulties to gaining support for unfamiliar actions based on interpretations of values and facts that are not explicitly part of organization's shared model. There not be the time needed for customary consensus-building efforts. There may not be clear recognition of the needed autonomy.

There may be unusual exposure to being evaluated in the light of biased hindsight. There may be problems in coordinating the activities of those involved in implementing the decision. These difficulties affect the ability to anticipate the consequences of taking various actions, as well as decision makers' ability to take those actions that seem right to them.

RESEARCH NEEDS: CREATING A SHARED MODEL

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The creation of explicit shared models demands several general intellectual skills. Each could be the source of problems and the object of research. Where procedures exist (or can be discovered) for enhancing those skills, there should be good opportunities to implement them widely (e.g., in the computer programs used for eliciting and presenting models). Something is known about the exercise of each of the skills.<sup>4</sup> If the same skills recur in the creation of many kinds of models, then learning more about them could provide some generally useful knowledge. They are:

Skill 1: identifying and characterizing the key components of the system being modeled.

Skill 2: identifying and characterizing the interrelations between those components.

Skill 3: estimating quantitative model parameters.

#### Skill 4: evaluating the quality of the model.

In the case of a probabilistic risk analysis, exercise of the first skill would include determining which pieces of physical equipment (e.g., valves, controls, piping) are vital to system performance and describing them in sufficiently precise terms as to allow further analysis. The second skill includes determining which malfunctions in System X need to be considered when studying the performance of System Y, and what the functional form of their relationship is. The third skill might include determining the probable distribution of failure rates for particular system components (e.g., valves, maintenance measures). The fourth skill involves actions such as determining the range of values to be used in sensitivity analyses, assessing the information yield of possible research activities, and determining how well the system is understood (as a prologue to deciding whether it is understood well enough for action to proceed).

Creating such engineering models can be seen as a special case of the general problem of eliciting information from experts. It differs from the perspective associated with what are usually called "expert systems." Here, the modeling language does not attempt to be a natural one. Rather, it is a flexible analytic language, capable of modeling a wide variety of situations and pooling the knowledge of diverse experts--if they can express themselves in the terms of the language. Thus, the core of the needed research programme is an examination of how people express their beliefs in the terms of

abstract languages, and how they interpret the expressions of others' beliefs in the models that they share.

As with "expert systems," these models can help users understand (and communicate) the nature of their own expertise. Models force one to be explicit and allow one to simulate the effect of varying assumptions on model performance. However, if the language is awkward, or imprecise, or inconsistently interpreted, then users may not know what they are talking about. If the syntax is unintuitive, then users may not understand the implications of the relations that they have described. In such cases, expertise couched in terms of true natural languages, with their deep dependence on tacit knowledge, may not ensure expertise with the modeling language. There even may be a role for interpreters, helping experts express what they know in terms that the language can accept.

As a small example of the possibility of such difficulties, (Fischhoff et al., 1978) two groups of experienced garage mechanics were asked judge the completeness of tree-like graphic depictions of possible reasons why a car might not stop. One group judged a fairly complete tree, the second a tree from which major systems (e.g., battery, ignition) had been pruned. Even though the pruning removed systems judged to include approximately 50% of problems, the pruned tree was judged to be almost as complete as the full one. The (pruned) systems that were out of sight were effectively out of mind. Although these experts clearly knew about the missing systems, they had difficulty interpreting that knowledge in the terms of the

model. Their expertise might have been better exploited by having them list specific instances of no-starts, rather than asking for direct estimates of completeness. A second set of examples lies in the research literatures documenting the difficulties that people have with testing hypotheses and discerning causal relations (Evans, 1982; Fischhoff and Beyth-Marom, 1983; Kahneman et al., 1982; Nisbett and Ross, 1980).

Understanding these properties of modeling languages is important to having realistic expectations from them. Improving people's fluency with them is critical to improving the quality of modeling and the ability of shared models to serve an organization's needs. From this perspective, what is needed, in effect, is an understanding of engineering design as a cognitive and social process, focused on these explicit expressions of it.

Every modeling language (like every other language, presumably) is better at capturing some kinds of situations than others. For example, most engineering languages are ill-suited to describing the actions of humans within a technical system (Hollnagel et al., 1986; Rasmussen and Rouse, 1981); economic techniques, such as cost-benefit analysis, are ill-suited to treating goods that are not traded directly in an unrestrained market; military intelligence analyses have more of a place for quantitative, tactical information (e.g., about what the enemy has) than for qualitative, strategic information (e.g., about what the enemy really wants). Such situations leave users with the difficult task of integrating two qualitatively

different kinds of information, differing in how readily they can be incorporated in the model. Research is needed into how to extend the range of modeling languages, and into how to help users deal systematically with those factors that are left out.

Once models have been created, they must be communicated, raising the question of who needs to know what. Some balance must be struck between telling too much and too little. One research approach to developing communication guidelines would come out of value-of-information analysis, asking what information effects the greatest difference in the expected value of the specific decisions that need to be made at different nodes (Raiffa, 1968). A complementary, cognitive approach would consider how broad and deep a picture people need to see in order to understand the interface between their own actions and those taken elsewhere. A third, more social approach would ask how people anticipate what others in the system know, so as to be able to interpret their actions (Gardenier, 1976; Metcalf, 1986).

After a model has been created, it must be updated, both as the system changes and as better information about it is received. Although the natural desire is always to be current, that can create problems of understanding and coordination. For example, with an evolving system, design changes that are introduced piecemeal may have system-wide ramifications that are never detected. Or, users may find it difficult to deal with a picture of the system that is never the same as when they last consulted it. Both of these kinds

of problems might be ameliorated by relying instead on periodic model-wide updating, at the price of letting the model become increasingly out of date as the last revision becomes more distant in time. Presumably, these "cognitive concurrency" problems, and their recommended treatments, will vary with the nature of the system and the changes.

Better models (and better use of existing models) would directly produce some better decisions, in those situations where action follows directly from the analysis of the facts. In other cases, the facts do not speak for themselves, but must be considered in the light of organizational policies. In such cases, there may be some place for decision aiding. The shared model could attempt to identify relevant policies and extract their implications for particular decision problems. To avoid the rejection that decision aids frequently have experienced, they would have to aid decisions without usurping decision-making responsibility. That calls, in part, for cognitive research (e.g., on how to display the assumptions and definitiveness of recommendations) and, in part, for social research (e.g., on how to justify aided decisions).

#### RESEARCH NEEDS: USING IMPERFECT SYSTEMS

The key to using imperfect systems is understanding their imperfections. In part, that is a question of factual knowledge about problems and their solutions. In part, that is a question of

appraising the limits to one's understanding of the system. That understanding is essential to being ready for surprises.

As mentioned earlier, considerable research has examined people's ability to assess the limits of their own understanding (Wallsten and Budescu, 1983). Typically, it has shown weak positive correlations between how confident individuals are in their own knowledge and how extensive that knowledge is. Although individuals are more knowledgeable when they are more confident, the relationship is quite imperfect. The most common overall tendency is toward overconfidence. Similar results have been observed in various settings, including some involving experts making judgments in their areas of expertise (Henrion and Fischhoff, 1986; Hynes and Vanmarcke, 1976) and some involving people's assessment of their understanding of technical systems (Fischhoff and MacGregor, 1986).

Although it could express itself as overconfidence in the reliability of a system, overconfidence in one's own understanding could also express itself in undue readiness to override a system and assume personal control. This has, for example, been the experience with attempts to automate various kinds of clinical diagnosis (Dawes, 1979). It is, therefore, important to know how accurately the operators and designers of a system are able to assess the extent of their own understanding of its operations. If these assessments are inaccurate, then it becomes important to know what cognitive processes are involved in assessing confidence (e.g., what cues do operators attend to? how do they weigh conflicting cues?). These

processes provide the points of leverage for improving their self-understanding (e.g., by training, restructuring information flows, formalizing the evaluation process).

One methodological obstacle to creating more realistic expectations is the difficulty of evaluating current expectations in operational settings. Some novel procedures are needed to extract expectations in a more or less online manner and then to compare them with actual system performance. It may be possible to meter performance in some way, or to create a "black box" that could be used to compare what operators thought was happening with what was really happening (following successful operations, as well as following unsuccessful ones).

Once the accuracy of expectations has been assessed, it must be communicated in ways that will appropriately shape operator (and designer) behavior. Research has shown that just telling people about a judgmental difficulty has little effect, without some instruction in how to think differently and in how to match abstract principles of thought and analysis to concrete problems (Fischhoff, 1982; Kahneman et al., 1982; Murphy and Winkler, 1984; Nisbett et al., 1983). Further research is needed in this aspect of helping people to use their minds better. It might include exploration of alternative statistics for characterizing either the system or observers' understanding of it. Information about system reliability could come in the form of various summary statistics, but also in the form of structural information that might provide insight into the

nature of problems as well as their magnitude. For example, it might be helpful to know about unresolved tensions in the design team, about the kinds of individuals (if any) who represented the perspectives of operators during the design process, about the number (or recency) of changes in design philosophy, about the state of the science underlying the design, and about the kind of external peer review to which the design was subjected. Whether such cues contain valid information is an analytical question. Whether that information can be used is an empirical behavioral question.

Expectations are the product of applying general beliefs to specific situations, as they are revealed by a system's external indicators. Normally, designers do everything possible to improve a system's transparency, that is, the chances that its status and operation will be interpreted appropriately. Where transparency is less than complete, however, operators need to understand a system's imperfections. The degree to which a system facilitates that understanding might be termed its metatransparency. In principle, transparency and metatransparency might be quite independent. In practice, they might even vary inversely. For example, summary presentations of current system status could facilitate getting a general feeling for the system, but obscure the raw observations that provide cues to the reliability of that summary. More generally, any refinement to a system can disrupt those finer points of its behavior that provide vital cues to judgments of its reliability. Thus, designers might consider when operators would be better off with a system that is harder to read but has better understood quirks. To

avoid such tradeoffs, they might be helped by research into how to introduce improvements without disrupting operators' local knowledge. This question is analogous to the questions of how to update models (discussed above) and how to avoid deskilling (discussed below).

One potential source of information regarding the limitations of a system is analysis of specific problems that it has had. Superior methods for incident analysis would be useful in this regard. One problem facing those methods is having mixed and conflicting purposes. Assigning blame, determining causality, and estimating the probability of future mishaps are missions that call for somewhat different and incompatible procedures. A second problem is the effect of hindsight bias, which can distort observers' interpretations of past events and even the memories of direct participants (Pew et al., 1982). A third obstacle to effective event analysis is ambiguity in the definition of events. For example, if incidents are defined too narrowly, then the lessons learned may ensure that a particular event sequence will not recur, but give the feeling that a whole class of events has been treated. Here, too, research is needed into the cognitive processes contributing to these problems and the procedures for overcoming them.

If events are defined precisely, then they may be amenable to theoretical analysis of the optimal breadth (or level) of analysis. As the category of event being studied broadens, a wider set of evidence becomes available, at the price of being able to reach less

precise conclusions and recommendations.<sup>5</sup> There are other behavioral aspects of dealing with imperfect systems that might benefit from analytical work. One is evaluating the sensitivity of decision making to different kinds of imperfection in information (Henricson, 1980; Krzysztofowicz, 1983; McCormick, 1981; von Winterfeldt and Edwards, 1982). Another is seeing how uncertainty about different aspects of the system accumulate to an overall estimate of its reliability (e.g., do they cancel or amplify one another). Another is providing some insight into the asymptotic level of reliability possible with systems of different levels of complexity (Perrow, 1984).

The ultimate expression of a lack of confidence is the decision to override a system over which the operator exercises supervisory control. It would be useful to have a fuller description of the override decision. What cues set it off? What steps are taken to confirm suspicions? How wide a set of system components (or operator actions) is called into question? What is the residual core of solid beliefs about the system? What cues are interpreted as demonstrating the return of control? How does one override decision affect subsequent behavior? In addition to descriptions of such decisions, one would want evaluations of their validity. Such evaluations might be available in existing system performance statistics. Or, operators' concerns might direct further research about the system. What operators do in the essentially novel situations created by a decision to override is the topic of the following section.

**DRAFT**

RESEARCH NEEDS: MANAGING NON-ROUTINE SITUATIONS

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Any system concerned with irregularities that pose serious threats to life and property must prepare for contingencies. One standard method for doing so is by contingency planning: possible problems are anticipated; the best solution to each is identified; those solutions are then incorporated in the training of operators. If successful, such exercises will lead to the decision regarding the appropriate response being made well before any contingency arises. Such deliberate decisions should benefit from the reduced time pressure, reduced (emotional) stress, and greater ability to recruit diverse experts (or even to conduct research) which comes with planning. In this view, operators will be relieved of the need to make decisions in non-routine situations, by making those situations familiar in the form of hypothetical experiences (even if those have yet to be experienced in reality). The decisions will be made by the contingency planners, leaving the operators to decide that some contingency has arisen and to decide which one it is. Then, the correct plan is accessed and executed.

Contingency planning requires a number of intellectual skills, each of which could benefit from study directed at ways to augment it. At the planning stage, these skills include the ability to imagine contingencies at all, the ability to elaborate their details sufficiently, the ability to generate alternative responses for evaluation, the ability to evaluate those responses critically in the hypothetical mode, and the ability to communicate the resultant

decisions to operators. At the execution stage, these skills include the ability for operators to diagnose their crisis situations in ways that allow them to access the correct plan. Failures at either of these stages may result in ineffective decisions or in operators wondering about the appropriateness of the decisions that they are required to implement.

These problems are analogous to those facing effective emergency training in simulators. One worries, for example, that those who develop simulator exercises, teach the textbook responses, and evaluate operators' performance share some deep misconceptions about the system's operation -- so that some critical contingencies are never considered. One also worries that spotting contingencies in the simulator might be quite different from spotting them in reality, where the system may have a different operating history or different social setting, or where operators are not as primed to expect problems (which typically come at enormously high rates in simulators). Understanding how people perform the component tasks in contingency planning might help decrease the number of non-routine decisions that have to be made (by making contingency planning more effective) and help assess the need for making non-routine decisions (by assessing the limits of contingency planning).

Such understanding might also help reduce the threats posed by undue reliance on contingency planning. One such threat is taking too seriously designers' idealizations of the system. Such models often provide a convenient basis for generating problems and

exercises. They may even be used to run automated simulators. However, it is in the nature of models that they capture but a piece of reality, often without a clear (and communicated) understanding of just what that piece excludes. In some cases, a model is actually made to do double duty, being used by designers to discover limitations of the system (leading to design changes) and by trainers as though it represented a stable, viable operating system.

More generally, one needs to worry about how routine system operations affect operators' ability to deal with non-routine situations. Inadvertently inculcating undue faith in a basic design that typically functions well would be one kind of interference, as would acting as though contingency planning had routinized the treatment of novel situations. Institutional threats might include failing to train for handling non-routine situations or failing to reward those who naturally have the skills for doing so (assuming that such skills could be discerned). The previous section suggested the possibility that the continuous introduction of design improvements or the polishing of synthetic data displays might disrupt operators' ability to "read" the system's state and to diagnose novel situations.

A general theoretical perspective for such research would be to consider the particular informational ecology in which judgment is acquired as a learned skill. Whenever that ecology changes, then there is some need to refine or alter judgmental skills, and some threat of negative transfer. A variant on this threat is deskilling,

whereby useful intellectual skills are allowed to wither or are neutralized by design features or changes. For example, as automation increases, operators will increasingly be faced with near-perfect systems, which fail so seldom that there is little opportunity to learn their idiosyncracies. The problems of getting operators "back in the loop" so that they can cope with non-routine decisions may require some reduction in automation and perfection. The result of deautomation might be an increased rate of errors overall, but a reduced rate of catastrophic ones (a result that would be hard to prove given the low rate of occurrence for catastrophes). Research on these issues would seem hard and important.

Whenever there is some significant chance that contingency planning will not do, some capability is needed for making decisions in real time, starting from a raw analysis of the situation (perhaps after going part of the way with an inappropriate contingency plan). Training (and rewarding) the relevant intellectual skills (i.e., basic decision-making abilities) would seem extremely important. Much more needs to be known about how it can be done. For example, operators need to be able to generate good options regarding what might be happening and what might be done about it. Studies of creativity, in vogue some years ago, ostensibly examined this question. However, they used rather simple tasks and rather simple criteria for evaluating options (typically, the more the better). One potential aid to testing those options that are generated would be on-line, real-time system simulators. These could help operators diagnose the situation that they see by simulating the situations

that would arise from various possible initiating conditions. They could also allow simulating the effects of various interventions. Getting such systems to work suggests some interesting computing and interface design problems.

A somewhat different kind of aid would be base-rate information describing typical performance of the system (or ones like it) under particular conditions. That information might describe, for example, what kinds of manipulations (in general) give one the best chance of being able to recover if they do not seem to be working, what manipulations provide the most diagnostic information about their failings, what are the best sources of information about current system status. Such statistical information might prove a useful complement to causal information about the system's intended operation. Its collection would represent an institutional commitment to learning from experience systematically.

It is often assumed that the choice of actions follows directly from diagnosing of the situation and anticipating of the effects of possible interventions. However, all decisions are contingent on objectives. Most organizations have complex objectives, some admitted and some implicit. Decision making can be paralyzed if the implications of those general values cannot be extracted for particular situations. It can be disastrous if the interpretations are inappropriate. Here, too, a mixture of analytical and behavioral work may help to improve that application and anticipate misapplications.

## CONCLUSIONS

### Research Management

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The topics described here were selected for their implications for the design and operation of equipment such as would be found in the space station and its support systems. They are, however, described in terms of the general psychological processes that they involve. As a result, they could be pursued both as part of the development work for specific NASA systems and as basic research issues examined in laboratory settings intended to represent low-fidelity simulations of the actual NASA environments. Similarly, NASA could contribute to concurrent research prompted by other systems that place similar intellectual demands on designers and operators. Such connections would help to ensure the transfer of technology from NASA to the general community concerned with automation.

Insofar as this research deals with problems relevant to other technologically saturated environments, it should be able to learn from developments there. One relevant trend is the increasing scrutiny that is being given to the quality of expert judgment in technical systems. Some of that interest comes from within, out of concern for improving the engineering design process. Other interest comes from outside, out of the efforts of critics who wish to raise the standard of accountability for technological problems. In the face of that criticism, expert judgment proves to be a particularly

vulnerable target. Although there is frequently great faith within a profession in the quality of its judgments, there is not that much of a research base on which to base a defense (Feyerabend, 1975; Morgan et al., 1981; Nelkin, 1984). Such research would have considerable basic, applied, and even political interest.

A second relevant trend is the introduction of computers into industrial settings. The creation of equipment has always carried an implicit demand that it be comprehensible to its operators. However, it was relatively easy for designers to allow a system to speak for itself as long as operators came into direct contact with it.

Computerization changes the game by requiring explicit summary and display of information (Hollnagel et al., 1986). That, in turn, requires some theory of the system and of the operator, in order to know what to show and how to shape the interface. That "theory" might be created in an ad hoc fashion by the system's designers. Or, there might be some attempt to involve designers with some expertise in the behavior of operators, or even representatives of the operators themselves (even in places where they do not have the high status of, say, pilots). A prejudice of this article, and others pieces written from a human factors perspective, is that concern over operability should be raised from the very inception of a project's development. Only in that way is it possible to shape the entire design with operability as a primary concern, rather than as a tack-on, designed to rescue a design that has been driven by other concerns. As a result, raising these issues is particularly suited

for a long-term development project, such as that concerning this working group and volume.

### Philosophy

A fundamental assumption of this chapter is that much of life can be construed as involving decisions (i.e., the deliberate choice among alternatives, often with uncertain information and conflicting goals). A corollary assumption is that the basic cognitive (or intellectual) skills involved in decision making have wide importance--if they can be understood and facilitated.

These are hard issues to study. However, even if they cannot be resolved in short order, system performance might be improved simply by drawing attention to them. A task analysis of where such skills arise can increase sensitivity to them, grant legitimacy to operators' complaints regarding problems that they are experiencing, and encourage a folklore of design principles that might serve as the basis for subsequent research.

The decision-making perspective described here is strongly cognitive, in part, because the decision theory from which it is drawn offers a widely applicable perspective and a well-defined set of concepts. As a result, there is a relatively high chance of results rooted in this perspective being generally applicable. Moreover, there may be some value to a general habit of characterizing decision-making situations as such. Within this

context, there is still place to ask about issues such as the effects of stress, tension, conflict, fatigue, or space sickness on these higher-order cognitive processes (Wheeler and Janis, 1980).

This perspective sees people as active in shaping their environment and their decision problems. It could be contrasted with an operation research-type perspective in which people are reduced to system components and behavioral research is reduced to estimating some performance parameters. Focusing on what people do, rather than on the discrepancy between their performance and some ideal, increases the chances of identifying interventions that will help them to use their minds more effectively.

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## NOTES

1. The chapters in this volume by Buchanan, Davis, Howell, Mitchell, and Newell provide other points of access to this literature.
2. The relationship between problem solving and decision making bears more discussion than is possible here, see National Research Council, 1986 for additional information.
3. In this particular case, there seems to be such generality, unless experience provides the sort of feedback needed to acquire probability assessment as a learned skill.
4. Fischhoff (in press) is an attempt to provide access to this literature, expressed in the context of the judgmental component of risk analyses for hazardous technologies.
5. Furby and Fischhoff (1986) discuss related issues in a very different context.

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ISSUES IN DESIGN FOR UNCERTAINTY:

A COMMENTARY ON THE

FISCHHOFF AND DAVIS PAPERS

William C. Howell

Department of Psychology

Rice University

Houston, Texas

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Reviewing the presentations of Drs. Davis and Fischhoff, one would be hard pressed to find critical omissions in the slate of issues set forth regarding human participation in the space station's judgment/decision/problem-solving requirements. The problem facing the R&D team, like that facing the future operators of the system itself, is deciding which of the plethora of options to address first -- and to what depth -- in the absence of complete knowledge. Agenda will have to be set, priorities established among research objectives (all of which seem worthy), and decisions made on when understanding has reached a sufficient (albeit far from ideal) level to move on to either development or the next agenda item.

The present discussion, therefore, will focus on some of these programmatic considerations. It would, of course, be presumptuous for anyone to prejudge the relative merit of research programs yet to be proposed for a moving target such as the evolving space station concept. Nonetheless, current knowledge is sufficient to begin the process so long as it is with the clear understanding that frequent stock-taking and consequent reorientation will undoubtedly be required as research findings accumulate, design decisions are made, and the entire system takes shape. Research never proceeds in as orderly a fashion as we anticipate in our plans and proposals because Mother Nature doesn't read them. One never knows when she will choose to reveal some important secret that will divert the whole process!

And finally, the discussion of priorities should in no way be construed as a call for serial research. The philosophy endorsed here is consistent with a theme that runs through the entire symposium: parallel research efforts must be carried out at various levels of specificity on a representative sample of the total problem space if the program is to evolve -- and continue to develop -- in the most efficacious manner. The pressure to focus too narrowly on the most well-defined or immediate problems is all too prevalent in undertakings of this magnitude having the level of public visibility that the space station enjoys. Many of the problems sure to arise "downstream" are in areas where the present knowledge base is at best primitive. Attention must be given now to expanding those knowledge bases if we are to avoid costly delays in development and/or costly design mistakes as the total system takes shape.

#### Model Building

Both presentations emphasize the importance of developing a conceptual model or set of models of the space station. Together, Davis and Fischhoff sketch out the essential features of such modeling and the kinds of research questions that must be addressed in order to make it useful. I shall not repeat their observations, except to note one point of contrast and to explain why I believe model building deserves a top priority.

First the contrast. Davis makes a distinction between aspects of the total system about which there is and is not sufficient information to construct models. Where it is deemed feasible, chiefly in the physical

domain, the trick is to make the models -- and the systems they represent -- "resourceful" and comprehensible. Where it is not, the issue becomes one of finding alternatives to modeling. Fischhoff, on the other hand, seems to have in mind a more comprehensive kind of modeling effort: one that encompasses a variety of domains and levels of understanding. Here the emphasis is on integrating what we know even incompletely, and providing a framework upon which to build new understanding.

Whichever concept one prefers, and I lean toward the latter, the research issues are largely the same. Both call for exploring new ways to capture and express properties of the system that will promote understanding across disciplines; both recognize that to do so requires a better grasp of certain cognitive functions than we now have. There are, in my view, at least four main reasons to emphasize a broad modeling effort (Meister, 1985).

First, the process of model building is the most expeditious way to organize our knowledge and ignorance, not only at the outset, but as the knowledge base grows and the system evolves. Assumptions, facts, parameter estimates, areas of uncertainty etc. can be clearly articulated; gaps that need to be filled, or estimates that need to be refined, can be identified. More than anything, a conceptual model can ensure that even the most pragmatic research has a better chance of contributing to the total effort. Taken literally, for example, the issues raised by Davis and Fischhoff cover virtually the entire domain of cognitive and social psychology. Were nature to take its course in these various research

areas (or even were NASA support to accelerate the overall progress), the odds of learning precisely what needs to be known at critical junctures in the space station's development are quite low. I shall have more to say on this point later. For present purposes, the argument is simply that model building is a useful technique for keeping the research efforts at all levels of generality properly focused. One can study confidence in judgement, or interpersonal tension, or hypothesis generation, or human problem solving tendencies, or what experts know and do, or any of the other general issues identified by the presenters in ways that are more or less likely to generalize to the space station situation. I see no inherent reason why an experiment designed to advance fundamental knowledge in one of these areas cannot be conducted in a space-station context as easily as in terms of weather forecasting, battle planning, livestock judging, or business management. A model is useful for specifying that context.

A second reason that model building merits the highest priority lies in its contribution to the ultimate development of tasks and procedures. The ways in which this contribution would manifest itself are well described in the two presentations. In essence it boils down to making reasoned design decisions from a system-wide perspective rather than from some parochial or purely traditional point of view -- be that an engineering, computer science, cognitive, biomedical, or even a humanistic perspective. It forces early attention to such critical matters as developing a common language and frame of reference within which the various specialists can function interactively. If there is one unique requirement for the successful achievement of this project's goal, it is

that barriers to the exchange of information and intelligence among units -- human-human, human-machine, machine-machine -- be minimized. Systems of the past have generally had to attack such barriers after the fact because of the initial dominance of one or another technical specialty. And they have done so with only limited success. Here the opportunity exists to "design in" features that can minimize barriers. Model development encourages this kind of thinking from the very outset -- provided, of course, it is not entrusted to only one technical specialty!

A third argument for the priority of model building is its obvious importance for training, and possibly even personnel selection. True, a model is not a simulation. Nevertheless, simulation at some level of fidelity must ultimately be constructed just as it has been for training on all the earlier projects in the space program. To the extent that the model organizes what is known and unknown at a particular stage, it permits development of simulations that have a greater likelihood of providing training that will transfer positively to the operational tasks. The kinds of uncertainties and unanticipated contingencies the human is apt to encounter in the space station are more likely to arise in a simulator based on a comprehensive modeling effort than they would be in a simulator designed to maximize purely technical fidelity. In the absence of a good conceptual model, the criterion of technical fidelity is almost certain to dominate. To use an extreme example, suppose the modeling effort identified a social phenomenon whose course of development extends over a period of months and whose appearance dramatically alters the way certain kinds of decisions are handled. Naturally, this would

argue for incorporating a several month duration requirement into the simulation even if the technical skills could be mastered in weeks. Without this social-process knowledge, the emphasis would almost certainly be on the face validity of the hardware and software components. In other words, comprehensive model development would increase the likelihood that any simulation would capture salient aspects of the operational tasks -- even some that cannot be completely anticipated and "programmed in." Similarly, it would provide a better sampling of the overall task domain and hence a more content-valid basis for setting personnel selection requirements.

In citing the virtues of model development for simulation and training, we should never lose sight of Fischhoff's warning against the possibility of overemphasizing the known to the exclusion of the unknown. Training that develops in operators a dependence on routines for handling anticipatable contingencies can be counterproductive when truly novel ones arise. However, thoughtful construction of a model can help obviate this problem by ensuring that the unknown is properly recognized. The real danger lies not in the attempt to build the most complete conceptual models we can, but in the temptation to build simulators that operate only within the domains where our knowledge is most complete.

Finally, model development encourages -- indeed forces -- the kind of interaction among specialists in the design phase that will have to occur among operational specialists if the program is to be a success. To mount a truly comprehensive modeling effort will demand creation of a shared language and knowledge base; the exercise will serve, in essence, as a

case study in multidisciplinary coordination as well as the source of a design product.

In a sense, all the other proposed research directions are subsumed under the objective of model development (or at least are directly related to it). As Davis points out, constructing an appropriately "robust" and "transparent" model requires judicious selection of which properties to include and ignore, and at what level of abstraction. How well that can be done is heavily dependent on our understanding of human cognitive processes in relation to the physical properties of the system. And it is largely to this end that the research suggested by Davis, Fischhoff, and indeed this entire conference is directed. Nevertheless, one can distinguish more narrowly defined issues, and some of these appear more promising or tractable at this point than others. Several that strike me as particularly deserving of a high priority are establishment of institutional values, manual override and standby capabilities, and transfer of training issues.

#### Establishing Institutional Values

Fischhoff explains that a critical issue facing decision makers in the operational system will be that of representing the organization's values in dealing with non-routine situations. One cannot anticipate all the circumstances that might arise that would require human judgment, but it is possible to define the value parameters along which those judgements would have to be made and the extent to which insitutional, crew, or individual value systems would take precedence.

Most decisions incorporate value and expectation considerations in one form or another (Huber, 1980; Keeney and Raiffa, 1976). There are a lot of ways to help objectify or improve the expectation element, but values are inherently subjective. This is why there are political systems, judicial systems, wars, and advertising agencies. Unless we can articulate the value system under which the decision maker is to operate -- or at least the general process by which s/he is to assign values -- s/he faces an impossible task. It is somewhat akin to that facing the medical community in its allocation of scarce and costly life-saving resources (such as organ transplants) to a much larger and multifaceted population of worthy recipients. Whose interests take precedence, and how are the value considerations to be weighed?

This issue is not an easy one to address, in part because it gets to the heart of the most sensitive, controversial, and politically charged aspects of any important decision domain. We do not like to make explicit the level of acceptable risk in air safety, nuclear power, or military confrontation (e.g. how many lives we are willing to sacrifice for some larger good). However, there is some implicit value system operating in any such decision, and research over the past decade has produced methodologies for helping to pin it down (Howard, 1975; Huber, 1980; Keeney and Raiffa, 1976; Slovic et al., 1980). Extension of these techniques, and perhaps development of others, to provide a common value framework for crews and individuals to carry with them into space is essential if decision-making is to be of acceptable quality. Indeed, without such a framework the concept of decision quality has no meaning.

The options are to face the issue squarely and develop a value framework in advance, or to leave it intentionally vague and ad hoc, thereby offsetting whatever progress is made toward improving decision quality through enhancement of expectation judgments.

### Understanding Override and Stand-by Capabilities

Clearly an important set of research issues centers around the idea that human judgment represents the last line of defense against the unanticipated. The ultimate decision that some automated subsystem is malfunctioning, or that some low probability or unclassifiable situation has arisen, and the skill to move quickly from a relatively passive to an active mode in response to it are critical elements of the human's role.

Both presentations address override and standby skill issues albeit in slightly different ways. For Davis, they fall within the category of "making the best of the situation," or what to do when we have no model. He speculates on alternative strategies, and suggests that we need to explore them, but is obviously more concerned with "making the best situation" -- increasing the robustness and transparency of the system and its models. For Fischhoff, these issues epitomize a central dilemma in the whole development process -- the tradeoff between using everything we know for aiding and contingency planning purposes, and preparing people to deal with the truly unknown. He argues that designing the system to maximize decision accuracy may not really be optimal when one considers the potential costs in human judgment facility. (Here, incidentally, is

another instance where the problem of establishing a unified value system becomes critical.)

What strikes me as particularly urgent about research on these issues is that we know just enough to worry, but not enough to say how they should be handled. For example we know about overconfidence bias and can easily imagine its implications for crisis decision-making, but we are far from understanding all the task and individual-difference parameters that govern its seriousness (Hammond et al., 1980; Howell and Kerkar, 1982). And we know even less about constructs such as creativity in either the individual or group context. Were we able to identify and measure such individual traits, we might include these measures in a personnel selection battery. And understanding group processes might suggest ways to offset deviant individual tendencies. Unfortunately, our present knowledge of group decision making does not allow us to predict with much certainty how group judgments will compare with individual ones (Huber, 1980; Retiz, 1977; Howell and Dipboye, 1986).

Similarly, it is fairly well established, as Fischhoff notes, that stand-by skills suffer from disuse as the human spends more and more time "outside the loop" in a monitoring capacity. This is particularly true for cognitively complex and dynamic systems. But how does one "stay on top of things" when active involvement becomes increasingly rare as more and more reliance is placed on automating decision functions? Is something as elaborate (and costly) as a totally redundant manual back-up ever justified simply for the purpose of maintaining stand-by capabilities? And even if that were done, would the human be able to

maintain a serious involvement knowing the status of his or her role? One need only take a look at NORAD operators doing their "canned" training exercises to appreciate the significance of this point! Would some other form of involvement do as well? For what decision tasks should some form of involvement be maintained? To answer questions such as these, more will need to be learned about stand-by capabilities in critical tasks of the sort that are likely to be automated or aided in the space station. Fischhoff's presentation does an excellent job of identifying the key questions.

Issues concerning the override function should be addressed early in the development process at a fairly basic level since more general knowledge is needed before it will be possible to articulate the most critical applied research questions. Stand-by skill maintenance, on the other hand, seems more appropriately addressed at an applied research level after it becomes clear what sorts of functions the human would be asked to back up.

#### Training for the Known and the Unknown

Issues of training and transfer are closely related to those of standby skill; in fact, the latter are really a subset of the former. The purpose of training is to establish habitual ways of thinking and acting in certain situations that are likely to improve individual or team performance whenever those situations arise. So long as one has at least some idea of what kinds of situations might develop, there is reason to hope that the right habits might be cultivated. But if one guesses wrong,

or the situation domain changes, or the habits that work well for the known situations turn out to be counterproductive for the unknown ones, obvious transfer problems arise. Since the unanticipated is by definition inaccessible for simulation or contingency planning, those charged with training development face the dilemma alluded to earlier. Too heavy an emphasis on the known or suspected task elements could develop habits that prove disastrous when something totally novel comes along. On the other hand, training that emphasizes the flexibility of response necessary to deal with novel situations could undermine the potential advantages of habitual behavior.

Advances have been made toward addressing this dilemma in recent research on fault diagnosis and problem solving (particularly in connection with complex process control systems, e.g. Moray, 1981; Rasmussen and Rouse, 1981). Still, as Fischhoff notes, there are a lot of fundamental questions that remain to be investigated before we can even begin to conceptualize how training ought to be structured in a systems as advanced as the space station. Once again, we have here a set of pressing issues on which some headway has already been made and research directions have been identified. For these reasons, I believe it merits a high priority in the overall research scheme.

To this point, my comments have focused exclusively on priority setting within the domain of research issues raised by the two presenters. To summarize, I believe the modeling effort should be an initial and continuing emphasis -- a framework within which many parallel streams of research activity can proceed coherently and purposefully. Of

those more narrowly defined issues, I consider the matter of establishing institutional values or value assessment techniques as primary, followed closely by the need to clarify the override function, to find ways to maintain intellectual standby skills (or define an optimal level of automation), and to train operators to deal with changing and unanticipatable circumstances.

There are two other programmatic issues that I would like to comment on briefly that were not an explicit part of either paper: individual differences, and the age-old basic vs. applied research controversy.

#### On Individual Differences

Both presentations suggest quite correctly that our designs must be geared to typical behavior -- of people in general, or potential operators, or "experts". The assumption is that there are commonalities in the way people approach particular decision problems, and our research should be directed toward understanding them. I agree. But I contend there is another perspective that has been all but ignored by decision theorists that might also contribute to the effectiveness of future decision systems. On virtually any standard laboratory problem, subjects will differ dramatically in both the quality of their performance and the way they approach it. True, the majority -- often the overwhelming majority -- will display a particular bias, heuristic, or preference on cue. But even in the most robust demonstrations of conservatism, or overconfidence, or representativeness, or non-transitivity there will be some subjects who don't fall into the conceptual trap. What we don't

know, in any broader sense, is whether these aberrations represent stable trait differences, and if so, what their structure might be and how they might be measured. There has been some work on risk aversion (Atkinson, 1983; Lopes, in press), information-processing tendencies (Schroder et al., 1967), and decision-making "styles" (Howell and Dipboye, 1986), but very little compared to the vast literatures on typical behavior.

I suspect, though I can't really prove it, that individuals differ consistently in their inclination to attend to, process, and integrate new information into their current judgments. Were this the case, it might be useful to have some means of indexing such tendencies. Speaking more generally, I believe research aimed at exploring the consistent differences in the way people approach decision problem is just as valid as -- though considerably more cumbersome than -- that concerned with similarities. It should be encouraged.

#### On basic and applied research strategies

At various places in the foregoing discussion I have suggested that certain issues might be attacked at a more basic or more applied level given the state of our current knowledge and the demands of the design problem in that area. I should like to conclude my discussion with some elaboration on this general strategic issue.

If there is one limitation on our understanding of judgment/decision processes, in my opinion, it is that of context specificity. Work on judgmental heuristics, diagnosis and opinion revision, choice anomalies,

group decision making, individual differences in judgment or decision, etc. each has developed using its own collection of preferred research tasks, strategies, and literatures (Hammond et al., 1980; Schroder et al., 1967). Consequently, it is not always possible to judge how far a particular principle will generalize or whether some human tendency is likely to pose a serious threat to performance in a particular system.

Nevertheless, as the two presentations have clearly demonstrated, these basic literatures provide a rich source of hypotheses and leads for consideration in an evolving program such as the space station. The judgmental heuristics and resulting biases cited by Fischhoff, for example, are indeed robust phenomena, principles to be reckoned with in shaping the space station environment. However, despite their ubiquity, such modes of cognition are more prominent in some contexts and under some conditions than others -- a point emphasized by Hammond in his "cognitive continuum theory" (Schum, 1985); and the seriousness of the consequent "biases" depends to some extent on one's definition of optimality (Hammond, 1981; Hogarth, 1981; Schroder et al., 1967; Phillips, 1984, Von Winterfeldt and Edwards, 1986).

Consider the overconfidence bias. One implication of this well established cognitive phenomenon is that decision makers would be likely to act in haste and believe unduly in the correctness of their action, a clearly dysfunctional tendency. Or is it? A common complaint in the literature on organizational management is that managers are all too often reluctant to act when they should (Peters and Waterman, 1982). Perhaps overconfidence may serve to offset an equally dysfunctional bias toward

inaction in this setting. Similarly, decisions must often be made under considerable uncertainty, and this will clearly be no less true of space station than of business or military decisions. However, once a decision is made, albeit on the basis of what objectively is only a 51% chance of success, is there not a certain practical utility in actually believing the odds are better than that? If, as often happens, the decision is not easily reversed, what is to be gained by second-guessing or "waffling", and is there not a potential for benefit through the inspiration of confidence in others? In some cases that alone can increase the "true" odds! The point is, overconfidence, like other human cognitive tendencies, may have functional as well as dysfunctional implications when viewed in a particular context (Hammond, 1981); and even then, its magnitude may be partly a function of that context. Thus the more clearly we can envision the context, the more likely we will be to generate the right research questions, and what that research adds to our basic understanding of overconfidence or other such phenomena will be no less valid than that done in other contexts. All judgment and decision research is done in some context; generalization accrues via convergence of evidence over a variety of contexts.

My basic point is this. The space station offers a very legitimate -- indeed, an unusually rich -- real-world context within which to explore a variety of "basic" and "applied" research questions concurrently. Properly coordinated, the combined effort holds considerable promise for advancing our understanding of fundamental judgment/decision processes in part because of the shared context. Three considerations would, I believe, promote such coordination.

First, as noted earlier, some effort should be made to encourage basic researchers to consider salient features of the space station situation in the design of their laboratory tasks and experiments. While it could be argued that putting any constraint at all on such work violates the spirit of "basic research," I believe some concessions can be made in the interest of increasing the external validity of findings without compromising the search for basic knowledge. Secondly, research of a strictly applied nature, addressing specific judgment/decision issues that must be answered in the course of modeling, simulation, and ultimately design efforts, should proceed in parallel with the more basic endeavors. In some cases, the question might involve choice of a parameter value; in others, identification of how subjects approach a simulated space-station task. Necessarily, such research would be less programmatic, more responsive to immediate needs, and more narrowly focused than the fundamental work.

Finally, and most importantly, NASA must do everything possible to ensure that the basic and applied efforts are mutually interactive. As hypotheses and generalizations are identified at the basic level they should be placed on the agenda of the applied program for test or refinement; as features are built into the evolving system concept, they should become salient considerations for the basic research effort; as questions of a fundamental nature arise in the course of the applied work, they should be incorporated into the basic research agenda.

This all sounds quite obvious and "old hat." Certainly it is the way DoD research programs, for example, are supposed to work (Meister, 1985). I submit, however, that no matter how trite the notion may seem, having closely coupled research efforts at basic and applied levels must be more than just an aspiration if the judgment/decision challenges of the space station project are to be met successfully. It must be planned and built into the very fabric of the program. The fact that the space station must develop by its own research bootstraps, as it were, permits little slippage and wasted effort. Yet the state of our knowledge does not permit neglect of either basic or applied research domains.

There are, of course, a number of ways this coordination of basic and applied work might be achieved ranging from centralized administrative control to large-scale projects that are targeted to particular sets of issues and encompass both basic and applied endeavors under one roof. I am not prepared to recommend a strategy. Rather, I suggest only that the issue is an important one, and one that deserves special attention at the very outset. How it is managed could spell the difference between enlightened and unenlightened evolution of the whole system regardless of how much resource is allocated to judgment/decision research.

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SESSION 4:

COMPUTER AIDED MONITORING & DECISION MAKING

SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

William C. Howell

## COMPUTER AIDED MONITORING & DECISION MAKING

### SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

Most of the points raised during the Session 4 and general discussion centered around two somewhat related issues:

1. the gap between behavioral (heuristic) and traditional (rule based) approaches to decision making, and
2. how to deal with shortcomings in one or the other that detract from system performance.

#### The Gap Issue

The observation was made that there seem to be two ways of thinking about decision problems, each with its own philosophy and research agenda, that are proceeding more or less independently. To some extent, it was pointed out, the two papers in the session highlight the differences between the two approaches. The question was whether, and if so how, they should be integrated or linked more closely.

Two conflicting views were offered. One was that since the differences are deeply rooted in their respective traditions and cultures, the barriers will not be broken down easily, and the anticipated payoff for NASA would probably not justify the time and cost necessary to bring about an integration. A number of other issues should take precedence over this one. The opposing view was that the two approaches should be

better integrated, probably can be if NASA puts the issue on its research agenda, and in fact is being attempted in a small way through research currently in progress in Fischhoff's lab.

Among the suggestions for an integrative approach were the whole domain of fuzzy logic and the bounded rationality concept (e.g. defining general goals and then "fiddling with the model at the margin as in 'satisficing'"). It was pointed out, however, that in the context of expert systems such approaches reduce to writing a lot of conditional rules over a large number of state variables. Thus one cannot summarize easily what the system will do over the full range of decision problems.

#### Applications, Or Dealing With Shortcomings

Several options were suggested for minimizing the effect of suboptimalities in human judgment. Training, while not universally effective in overcoming biases, has produced some notable successes (e.g. weather forecasters). The key may well lie in the proper design of training programs (something that merits a continuing research effort). Increasing the trainee's sophistication in statistical concepts, however, is clearly of little help.

Aiding in its various forms and with its inventory of existing models has its place but also has limitations. Multiattribute utility theory, decision analysis, etc. are useful for solving well defined problems, but "bring no knowledge to the party." Often their logic is not transparent to the user and critical factors may be omitted. Thus their output may

not be satisfactory in either an absolute sense or as perceived by the user. When it conflicts with human intuition there is a problem, particularly if the human doesn't understand the logic. User acceptance of even improved decisions becomes problematic.

One approach to dealing with these deficiencies in the aiding models was advocated by Davis: find out what is missing and build it in. Intuition and creative thinking are not magic, but rather, "undiscovered rationality." Research should try to expose that rationality (or reasoning) and apply it in creating more robust models, as well as more transparent ones. To the extent that the research succeeds, it should be incorporated into training as well as aiding applications, and the result could be better decisions and greater acceptance of those decisions by users (who would now be more likely to appreciate the logic).

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SESSION 5:

TELEPRESENCE & SUPERVISORY CONTROL

Paper: Thomas Sheridan, MIT

Paper: Lawrence Stark, University of California

Discussant: Antal Bejczy, Jet Propulsion Laboratory

TELEOPERATION, TELEPRESENCE, AND TELEROBOTICS:

RESEARCH NEEDS FOR SPACE

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Thomas B. Sheridan

Massachusetts Institute of Technology

Cambridge, Massachusetts

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## INTRODUCTION

### The Need and the Dilemma

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One of the dramatic challenges posed by space is versatile inspection and manipulation remotely operated by man. Some people within and outside NASA would like to automate everything but cannot - because so many tasks are unpredictable and therefore not doable by special-purpose or preprogrammable machines, or are one-of-a-kind such that dedicated automatic devices to do them are too costly in weight and dollars. So human perception, planning and control are required. But to place man physically there is constrained by hazard and high cost of life support. Remote inspection and manipulation by man, on the other hand, poses serious problems of her getting sufficient sensory information and controlling with sufficient dexterity.

Artificial sensing, intelligence and control can help. Unfortunately we have hardly begun to understand how to integrate human and artificial brands of sensing, cognition and actuation. One thing is clear, however: to cast the problem in terms of humans versus robots is simplistic, unproductive and self-defeating. We should be concerned with how they can cooperate.

## Definitions

Teleoperation is extension of a person's sensing and manipulating capability to a location remote from him. A teleoperator includes at the minimum artificial sensors, arms and hands, a vehicle for carrying these, and communication channels to and from the human operator.

Telepresence is the ideal of sensing sufficient information about the teleoperator and task, and communicating this to the human operator in a sufficiently natural way that she feels herself to be physically present at the remote site. A more restrictive definition requires, in addition, that the teleoperator's dexterity match that of the bare-handed human operator.

Robotics is the science and art of performing, by means of an automatic apparatus or device, functions ordinarily ascribed to human beings, or operating with what appears to be almost human intelligence (adapted from Webster's 3rd Intl. Dictionary).

Telerobotics is a form of teleoperation in which a human operator acts as a supervisor, communicating to a computer information about task goals, constraints, plans, contingencies, assumptions, suggestions and orders, getting back information about accomplishments, difficulties, concerns, and, as requested, raw sensory data - while the subordinate teleoperator executes the task based on information received from the human operator plus its own artificial sensing and intelligence. Accompanying the human supervisor is a computer which can communicate, integrate, assess,

predict, and advise in human-friendly terms; at the site of the telerobot is a computer which can communicate with the human-interactive computer and effect control using the artificial sensors and effectors in the most efficient way. One human-computer command station can supervise many telerobots.

Supervisory control in the present context is mostly synonymous with telerobotics, referring to the analogy of a human supervisor directing and monitoring the activities of a human subordinate. Supervisory control does not necessitate that the subordinate person or machine be remote.

#### Early History

Prior to 1945 there were crude teleoperators for earth moving, construction and related tasks. About that time the first modern master-slave teleoperators were developed by Goertz at Argonne National Labs. These were mechanical pantograph mechanisms by which radioactive materials in a "hot cell" could be manipulated by an operator outside the cell. Electrical and hydraulic servomechanisms soon replaced the direct mechanical tape and cable linkages (Goertz, 1954), and closed circuit television was introduced, so that now the operator could be an arbitrary distance away. Soon telemanipulators were being attached to submarines by the Navy and used commercially by offshore oil extraction and cable-laying firms to replace human divers, especially as operations got deeper. By the mid 50's technological developments in "telepresence" (they didn't call it that at the time) were being demonstrated (Mosher, 1964; Johnsen and Corliss, 1967; Heer, 1973). Among these were: force reflection

simultaneously in all six degrees of freedom; hands with multi-jointed fingers; coordinated two-arm teleoperators; and head-mounted displays which drove the remote camera position and thereby produced remarkable visual telepresence.

By 1965 experiments in academic research laboratories had already revealed the problems of telemanipulation and vehicle control through time delay (Ferrell, 1965), and the early lunar teleoperator Surveyor demonstrated the problems vividly in an actual space mission. Touch sensing and display research was already underway (Strickler, 1966) though there was little interest in teletouch at that time. Soon thereafter supervisory control was shown to offer a way around the time delay problem, and also to have advantages even without time delay in the communication channel, where, in order to avoid collision or dropping grasped objects, quicker teleoperator reaction time was needed than the distant human operator could provide (Ferrell and Sheridan, 1967).

Though the NASA nuclear rocket project mounted a major effort in teleoperator development in the 1960's, after that program was cancelled and throughout the 1970's there was little support for space teleoperation or telerobotics. By 1970, however, industrial robotics was coming into full swing, for Unimation, GE and a handful of other American, Japanese and Scandinavian manufacturers had begun using relatively simple assembly-line robots, mostly for spot welding and paint spraying. By 1980 industrial robots had become graced by wrist force sensing and primitive

computer vision, and push-button "teach pendant" control boxes were being used for relatively simple programming from the shop floor.

#### Overview of Current Status

To outward appearances six-degree-of-freedom, force-reflecting, serial-link electrical or hydraulic master-slave manipulators have changed little in forty years. There are a few new and promising mechanical configurations of arms and multi-fingered hands in laboratories, but as yet they are unproven in practical application. Video, driven by a demanding marketplace, is now of high quality and miniaturized, and digitization and simple recognition processing of video images is fast and inexpensive. We have a variety of touch (surface contact and pressure array) sensors available in the laboratory, but as yet little understanding of how to use these sensors. In teleoperation depth perception remains a serious problem, but there is promising research on several fronts. We still have not achieved fine, dexterous telemanipulation with high fidelity feedback as implied by the term "telepresence".

As yet there is no satisfactory control theory of manipulation as an integrated sensory-motor control activity, but new theories have been developed for manipulation task-analysis from an AI perspective, for kinematic-dynamic control of complex linkages, and for force-displacement hand-environment impedance. We still think of controlling manipulator arms and the vehicles which carry them as separate activities; we haven't learned to combine the two (though infants do it with ease). We have

demonstrated simple human-supervised, computer-aided teleoperation in a number of ways, but our understanding of human-computer cooperation is very primitive, hardly commensurate with the label "telerobot" we employ with such abandon.

#### SPECIFIC AREAS IN WHICH NEW RESEARCH IS NEEDED

Research needs are discussed in four categories: (1) telesensing, (2) teleactuating, (3) computer-aiding in supervisory control, and (4) meta-analysis of human/computer/teleoperator/task interaction. Some recent and current research is cited.

#### Telesensing

My colleague, Dr. Stark, who is an MD and more sense-able than I, will deal more extensively with this category, particularly with vision, the most important human sense, and with the needs and possibilities in virtual displays and controls, depth perception, and other significant needs in teleoperator research.

I would like to comment about resolved force, touch, kinesthesia, proprioception, and proximity - five critical teleoperator sensing needs which must be recognized as being different from one another. These five, together with vision, are essential to achieve the ideal of "telepresense". For each it is important to understand how the human normally functions, and then to understand how the appropriate signals can be measured by artificial transducers and then displayed to the human

operator and/or used by artificial intelligence in a way helpful to the human operator.

Resolved force sensing is what the human body's joint, muscle and tendon receptors do to determine the net force and torque acting on the hand, i.e., the vector resultant of all the component forces and torques operating on the environment. In force reflecting master-slave systems this is measured either by: (1) strain gage bridges in the wrist (so-called wrist-force sensors); (2) position sensors in both master and slave, which, when compared, indicate the relative deflection in six DOF (which in the static case corresponds to force); (3) electrical motor current or hydraulic actuator pressure differentials. Display of feedback to the operator can be straightforward in principal; in force-reflecting master-slave systems the measured force signals drive motors on the master arm which push back on the hand of the operator with the same forces and torques with which the slave pushes on the environment. This might work perfectly in an ideal world where such slave-back-to-master force servoing is perfect, and the master and slave arms impose no mass, compliance, viscosity or static friction characteristics of their own. Unhappily, not only does reality not conform to this dream; it can also be said that we hardly understand what are the deleterious effects of these mechanical properties in masking the sensory information that is sought by the operator in performing telemanipulation, or how to minimize these effects. At least, thanks to computer coordinate transformation, it has been shown that master and slave need not have the same kinematics (Corker and Bejczy, 1985). Force reflection can also be applied to a rate-control joystick (Lynch, 1972) but it is less clear what the advantages are.

Touch is the term used sloppily to refer to various forms of force sensing, but more precisely to refer to differential pressure sense of the skin, i.e., the ability of the skin to detect force patterns, with respect to displacement both tangential and normal to the skin surface, and to time. The skin is a poor sensor of absolute magnitude of force normal to the surface and it adapts quickly. There are now a few instruments for artificial teletouch; most of these have much coarser spatial resolution than the skin, though a few of the newer ones utilizing optics have the potential for high resolution (Harmon, 1982; Schneiter and Sheridan, 1984). A major research problem for teletouch is how artificially sensed pressure patterns should be displayed to the human operator. One would like to display such information to the skin on the same hand that is operating the joystick or master arm which guides the remote manipulator. This has not been achieved successfully, and most success has been with displaying remote tactile information to the eyes using a computer-graphic display, or to skin at some other location.

Kinesthesia and proprioception are terms often used together, at least in part because the same receptors in the human body's muscles and tendons mediate both. Kinesthesia literally is the sense of motion and proprioception is awareness of where in space one's limbs are. Telekinesthesia and teleproprioception are particularly critical because, as telemanipulation experience has shown, it is very easy for the operator to lose track of the relative position and orientation of the remote arms and hands and how fast they are moving in what direction. This is particularly aggravated by his having to observe the remote manipulation

through video without peripheral vision or very good depth perception, or by not having master-slave position correspondence, i.e., when a joystick is used. Potential remedies are: multiple views; wide field of view from a vantage point which includes the arm base; and computer-generated images of various kinds (the latter will be discussed further below). Providing better sense of depth is critical to telemanipulation in space.

Proximity sensing is not something humans normally do except by vision, but cats do it by whiskers or olfaction (smell), and bats and blind persons do it by sound cues or vibrations felt on the face. Sonar, of course, will not work in space. Electromagnetic and optical systems can be used for measuring proximity (close-in ranging) to avoid obstacles or decide when to slow down in approaching an object to be manipulated (Bejczy et al. 1980). Such auxiliary information can be displayed to the eyes by means of a computer-graphic display, or, if the eyes are considered overloaded, by sound patterns, especially computer-generated speech. We need to understand how best to use such information in space.

#### TELEACTUATING

It was stated in the previous section that we know relatively little about certain types of remote sensing, i.e., both artificial sensing and display to the human operator controlling the teleoperator (this in spite of knowing a great deal about human sensing per se). Remote actuation (in which terms we include control in the conventional sense) poses an even larger problem, since it combines motor actuation with sensing and decision-making, and it can be said we know even less about this, except

for the practical knowledge we have from operating the kinds of teleoperators that have been around for a number of years, mostly in nuclear hot-laboratories and for undersea oil operations. Again, comments are offered in a number of specific categories where some research is ongoing but much more needs to be done. The control problems in this category, where computer interaction per se is not the principal issue, apply to both direct and supervisory control.

Multi-degree-of-freedom end-effectors seem a most obvious need, as evidenced by our own human hands, but the sad fact is that these have not been developed beyond a few laboratory prototypes. Commercial manipulators tend to have simple parallel-jaw grippers, and a few have claws, magnetic or air-suction gripping mechanisms, or special purpose attachment devices for welding, paint spraying or other special-purpose tools. Though parallel-jaw gripping seems the most obvious function for a one DOF end-effector, it is not yet clear what a second DOF might be for, or a third, etc. Multi-fingered devices such as those by Salisbury (1986) or Jacobson (1987) will help us answer these questions. At the moment fear of losing objects in space seems to militate against general purpose grippers; that could change in the future. Modern computer-graphic workstations begin to offer the hope of studying problems like these by computer simulation without having to build expensive hardware for every configuration and geometric relationship to be tested.

Two-arm interaction is a necessity for much human manipulation (it has become standard for nuclear hot-lab manipulators), but we rarely see it in industrial or undersea teleoperators. Part of this problem is to get the

most out a given number of degrees-of-freedom. For example, instead of having a single six-axis arm operating on one body relative to a second body (or base), one might accomplish the same by having a three DOF "grabber arm" position the body so that a second, say, three DOF arm can work in coordinated fashion to perform some assembly task. Industrial robot experience shows that two three DOF arms are likely to be simpler and cheaper than one six-DOF arm. This has not been implemented in space applications; the problem needs research.

Redundant DOF Hand-arm-vehicle coordination is a serious problem, and actually a need for any kinematic linkage of more than six DOF which must be controlled in a coordinated way. This is largely an unsolved theoretical problem, at least in part because the number of configurations which satisfy given end-point position/orientation constraints is infinite. One tries to select from among these solutions to minimize energy or time or to avoid certain absolute positions of the joints, or to prevent singularities, etc., but the mathematics is formidable. One arm of three and one of four DOF make for such redundancy, but perhaps even more important, so does a vehicle thrusting in six DOF with an attached arm of even one DOF. We humans coordinate movements of our own legs, arms, and bodies (many redundant DOF) without difficulty, but just how we do it is still a relatively well-kept secret of nature.

Multi-person cooperative control is one way to control a complex multi-DOF teleoperator - where each of several operators is responsible for maneuvering a single arm or vehicle in relation to others. Is this best or is it better to have a single operator control all DOF of both

vehicle and arm? We really don't know. Results from simple tracking experiments suggest that control of multiple independent tasks is very difficult for one person. When the degrees of freedom of a task are closely coupled and/or must be coordinated to achieve the task objectives, that can be relatively easy provided proper control means are provided - but up to how many DOF? It is surprising how little research is available in this area.

Adjustable impedance of master and/or slave is a promising way of making a master-slave teleoperator more versatile than if the compliance-viscosity-inertance parameters remained fixed (Raju, 1986). A carpenter may carry and use within one task several different hammers, and a golfer many clubs, because each provides an impedance characteristic appropriate for particular tasks which are expected. Carrying many teleoperators into space may be avoided by making the impedance between slave and task and/or between human and master be adjustable. We have hardly begun to understand this problem, and have much to learn.

Interchangeable end-effector tools is another way to accomplish versatility, and of course is precisely what carpenters, surgeons or other craftsmen use. Future space teleoperators may have a great variety of special tools for both modifying and measuring the environment. It is not clear how to make the trade between special and general purpose end-effectors.

Task-resolved manipulation means performing standard or preprogrammed operations (e.g., cleaning, inspecting, indexing a tool) relative to the

surface of an environmental object (Yoerger, 1986). This means sensing that surface in the process of manipulating and continually performing coordinate transformations to update the axes with respect to which the operations are being done. This is an extension of end-point resolution - ability to command the finger to move in a desired trajectory without having to worry about how to move all the joints in between.

Force-feedback with time delay has been shown both theoretically and experimentally not to work if the force is fed back continuously to the same hand as is operating the control, for the delayed feedback simply forces an instability on the process which the operator might otherwise avoid by a move-and-wait strategy or by supervisory control (Ferrell, 1966). Yet it seems that forces suddenly encountered or greater than a preset magnitude might be fed back to that hand for a brief period, provided the forward gain were reduced or cut off during that same brief period, and the master then repositioned to where it was at the start of the event with no force-feedback.

#### Computer-aiding in Supervisory Control

Computers may be used for relatively "low-level" computations in many of the telesensing/display and teleactuation modes described above. There are a number of other teleoperation research problems in which the human-computer interaction is the important part. These include computer simulation, computer-based planning/decision-aiding, and computer-aided command/communication/control in various mixes. All of these are part of supervisory control by a human operator of a telerobot.

# DRAFT

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Off-line, real-time, human-operable ("flyable") <sup>simulation of</sup>

teleoperation for research, engineering or training has barely begun to be viable. This is because of the complexity of simulating and displaying the vehicle plus the arm and hand plus the manipulated object plus the environment, having all degrees of freedom operate, with removal of hidden lines, and so on. Even nominally high-quality computer-graphics machines have trouble with generation of such complex displays in real time. We can come close today, but since computer power is the one thing that is bound to improve dramatically over the course of the coming few years, we might pay attention to the many possibilities for using computers as a substitute for building expensive hardware to perform man-machine experiments and evaluate new design configurations. There are serious problems to simulate the full dynamics of multi DOF arms and hands. There are problems to be solved to make simulated teleoperators grasp and manipulate simulated objects. There are many problems to get high quality pictures (in terms of resolution, frame rate, gray-scale, color, etc.) Telepresence is an ideal in simulators just as it is in actuality. In fact, to enable the human operator to feel he is "there" when "there" exists nowhere other than in the computer poses a particularly interesting challenge.

On-Line in-situ planning simulators might be used "in the heat of battle" to try out maneuvers just before they are committed for real action (and real expenditure of precious resources in space). In this case commands would be sent to the computer-based model of the vehicle and/or manipulator and these would be observed by the operator

prospectively, i.e., before further commands are given (as compared to the retrospective state estimation case to be described below). Commands (supervisory or direct) would be given to the simulation model but not to the actual process, the model results would be observed, and the process could be repeated until the operator is satisfied that he knows what commands are best to commit to the actual process. There are possibilities for having the simulator "tract" the movement of the actual process so that any on-line tests could start from automatically updated initial conditions. The problem of what to control manually and what to have the computer execute by following supervisory instruction is something that cannot be solved in general but probably must be decided in each new context; the on-line planning simulator might be a way to make this happen.

On-line simulation for time-delay compensation is appropriate only to direct control, and is not necessary for supervisory control. Here the commands are sent to the model and the actual system at the same time. The model's prediction (e.g., in the form of a stick figure arm or vehicle) can be superposed on top of the actual video picture delayed in its return from space. The operator can observe the results from the model immediately (before the time delay runs its course), thereby be much more confident in his move before stopping for feedback, and thus save several "move-and-wait" cycles. These techniques have been demonstrated for models of the manipulator arm (Noyes and Sheridan, 1984), but not yet for the manipulator arm and controlled vehicle in combination. When the motion of vehicles or other objects not under the operator's control can be predicted, e.g., by the operator indicating on each or several

successive frames where certain reference points are, these objects can be added to the predictor display. With any of these planning/prediction aids, the display can be presented from any point of view relative to the manipulator/vehicle - a feat which is not possible with the actual video camera.

State measurement/estimation/display has potential where all information about what is going on "right now" is not available in convenient form, or where measurements are subject to bias or noise, or multiple measurements may conflict. The purpose is to provide a best estimate of the current situation or "state" (values of key variables which indicate where the telemanipulator end effector is relative to reference coordinates or to environmental objects of interest, what are the joint angles and joint angle velocities, what is the level of energy or other critical resources, and so on) and display this to the human operator in a way which is meaningful and usable by him for purposes of control. This may mean combining information from multiple measurement or data-base sources, then debiasing this information to the extent that can be done (in light of available calibration data), and factoring in prediction of what the state should be based on knowledge of what recent inputs were and what are the likely system responses to these inputs. A complete state estimation yields a "best" probability density distribution over all system states. Much theory is available on state estimation but there has been almost no application to space teleoperation. Some research has shown that human operators are unable to assimilate state information that is too complex, and tend to simplify it for themselves by estimating averages and throwing away the full distribution, or at least

by using some simple index of dispersion, or in the case of joint distributions over two or more variables by considering only the marginal distributions, or even simplifying to point estimates on the independent variables (Roseborough, 1986). Research is needed on how to provide the operator all that can be got from state estimation and how to display this in a meaningful way.

Supervisory command languages must be developed especially for space teleoperators. We have a good start from industrial robot command languages (Paul, 1981) and from the few experimental supervisory command languages which have been developed in the laboratory (Brooks, 1979; Yoerger, 1982). We must understand better the relative roles of analogic instruction (positioning a control device in space, pointing, demonstrating a movement) and symbolic instruction (entering strings of alphanumeric symbols in more or less natural language to convey logic, description, contingencies, etc.). Clearly in everyday discourse we use both analogic and symbolic coding in communicating with one another, especially in teaching craft skills, which seem to relate closely to what teleoperation is. Both communication modes must be used in communicating with a telerobot. The telerobot usually starts with little or no "context" about the world, which objects are which and where they are in space. For this reason, it is necessary to touch objects with a designated reference point on the teleoperator, to point with a laser beam or otherwise to identify objects (perhaps concurrently with giving names or reference information symbolically), and to specify reference points on those objects. Recent progress in computer linguistics can contribute much to supervisory command language.

Voice control and feedback, for all the times it has been suggested as an interesting telemanipulation research topic in recent years, has seen very little systematic research. Voice command probably has the most promise for giving "symbolic" commands to the computer (in contrast to the normal "analogic" or geometric isomorphic commands which the master-slave or joystick provides). Vocal symbolic commands might be used to reset certain automatic or supervisory loops such as grasp force, or to set control gain, master-slave amplitude or force ratio, or to guide the pan, tilt and zoom of the video cameras (Bejczy et al., 1980).

Aids for failure detection/identification/emergency response are particularly important since in a complex system the human operator may have great difficulty knowing when some component has begun to fail. This can be because the component isn't being operated and hence there is no abnormal variable indicated. Alternatively, if it is being operated, the variables being presented as abnormal could have resulted from an abnormality well upstream. Finally, the operator can simply be overloaded. Many new failure detection/diagnosis techniques have been developed in recent years, some of them involving Bayesian and other statistical inference, some involving multiple comparisons of measured signals to on-line models of what normal response should look like, and so on. Failure detection/diagnosis is a critical part of supervisory control, where the operator depends on help from the computer, but himself plays ultimate judge. This may be a prime candidate for the use of expert systems.

## Meta-analysis of Human/Computer/Teleoperator/Task Interaction

Abstract theory of manipulation and mechanical tool-using has been surprisingly lacking. Control engineering, as it developed through the 1940-60 period, never really coped with the complex sequential dependencies of coordinating sensory and motor activities to perform mechanical multi-DOF manipulation tasks. Only when industrial robot engineers began to face up to how little they knew about how to do assembly did the need for a theory of manipulation become evident. Somehow it seems reasonable that the syntax of manipulation is analogous to that of natural language (i.e., tool-action-object corresponds to subject-verb-object, with appropriate modifiers for each term), since both are primitive human behaviors. It then seems a small step to apply computational linguistics to manipulation. But little of this has been done as yet.

Performance measures and assessment techniques need to be developed for teleoperation. At the moment there are essentially no accepted standards for asserting that one telemanipulator system (of hardware or software or both) is better or worse than some other. Of course to some extent this is context dependent, and the success will depend upon specific mission requirements. But there have got to be some generic and commonly accepted indices of performance developed which could be used to profile the capabilities of a teleoperator vehicle/manipulator system, including factors of physical size, strength, speed, accuracy, repeatability, versatility, reliability, etc. One worries whether even terms such as accuracy, repeatability, linearity, and so on are used in a

common way within the community. No one is asking for rigid standardization, but some commonality across tests and measures appears necessary to avoid great waste and bureaucratic chaos.

Direct experimental comparisons between astronauts performing hands-on in EVA and teleoperators, performing either in direct or supervisory-controlled fashion, must be done on a much more extensive and scientifically controlled scale, making use of both the manipulation theory and the generic performance measures to be developed. These experiments should be performed first on the ground in laboratories or neutral buoyancy tanks, much as Akin (1987) has begun, then in space on shuttle flights (e.g., EASE experiments), and eventually on the space station itself.

#### CONCLUSIONS

A number of research topics have been proposed, all seen as critical for the development of needed teleoperator/telerobotic capability for future space station and related missions. These have been presented in the areas of: (1) telesensing (with the longterm goal of telepresence); (2) actuation (with the long term goals of versatility and dexterity); (3) computer-aiding in supervisory control (with the long term goals of providing better simulation, planning and failure detection tools, and telerobots which are reliable and efficient in time and energy); (4) meta-theory of manipulation (with the long-term goals of understanding, evaluation, and best relative use of both human and machine resources).

Telerobotics, as much as any other research area for the space station, has direct research transferability to the non-government sector for use in manufacturing, construction, mining, agriculture, medicine and other areas which can improve our nation's productivity.

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TELEROBOTICS FOR THE EVOLVING SPACE STATION  
RESEARCH NEEDS AND OUTSTANDING PROBLEMS

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Lawrence Stark

University of California  
Berkeley, California

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## INTRODUCTION

The definition of telerobotics (TR) has not yet stabilized nor made the standard English language dictionary. I tend to use telerobotics as meaning remote control of robots by a human operator using supervisory and some direct control. Thus, this is an important area for the NASA evolving space station. By robot, I mean a manipulator/mobility device with visual or other senses. I do not name manipulators, as in many industrial automation set-ups, robots even if they can be flexibly programmed; rather calling these programmable manipulators. Our own laboratory at the University of California, Berkeley, has been involved in problems in display of information to the human operator, in problems of control of remote manipulators by the human operator, and in communication delays and band-width limitations as influencing both control and the display. A number of recent reviews have appeared with discussions of the history of telerobotics beginning with nuclear plants and underseas oil rigs.

### THREE SIMULTANEOUS RESEARCH DIRECTIONS

I believe that we should engage in triplicate or three way planning. It is important to carry out our research to accomplish tasks (i) with man alone, if possible, such as in EVA (extravehicular activities), (ii) with autonomous robots (AR), and (iii) with telerobotics. By comparing and contrasting the research necessary to carry out these three approaches, we may clarify our present problems. (See Table 1)

There are problems using man alone. The space environment is hazardous. It is very expensive to have a man in space; NASA must have quite adequate cost figures obtained from the demonstration projects that have already been accomplished with the shuttle program. We may also need a higher quality of performance than man alone can provide in terms of strength, resistance to fatigue, vigilance, and in meeting special problems. For example, if the space suit is not of constant volume under flexible changes of the limbs, then a great deal of strength is used up just in maintaining posture.

Problems with autonomous robots lie in our not having mastered the technology to build them and have them perform satisfactorily. They are not yet available! Indeed, designs are not yet fixed and it is not certain how feasible they will be, especially in terms of robustness and reliability.

Therefore, we can see that telerobotics is a viable leading edge technology. However, all three directions should be intensively pursued in research and development, especially for the next stages of the evolving space station planning.

#### SPACE STATION TASKS

One of the major roles that NASA can play is to hypothesize tasks for the evolving space station. In this way research regarding the design of telerobots to accomplish these tasks can be guided. For a list of seven groups of tasks see Table 2.

As I will consider later, it is important to distinguish between those tasks unique to the NASA/evolving Space Station and those with "industrial drivers" that will accomplish development of new technologies in hopefully a superior fashion and thus enable conservation of limited NASA resources.

#### PROBLEMS IN TELEROBOTICS

First I overview problems in telerobotics: those concerning displays, vision and other senses (Table 3) and those dealing with control and communication (Table 4).

In each table, I start with basic properties of the human operator and end up with planned capabilities of autonomous robots. In between, I try to cover what knowledge exists now in our field of telerobotics.

#### Experimental Set-Up for Three-Axis Pick-and Place Tasks

A teleoperation simulator constructed with a display, joysticks, and a computer enabled three-axis pick-and-place tasks to be performed and various display and control conditions evaluated (Figure 1). A vector display system (Hewlett-Packard 1345A) was used for fast vector drawing and updating with high resolution. In our experiments, displacement joysticks were mainly used, although in one experiment a force joystick was used to compare with a displacement joystick. An LSI-11/23 computer with the RT-11 operating system computer was connected to the joystick outputs through 12-bit A/D converters, and to the vector display system through a 16-bit parallel I/O port.

A typical presentation on the display screen for three-axis pick-and-place tasks included a cylindrical manipulator, objects to pick up, and boxes in which to place them, all displayed in perspective (Figure 2). Since perspective projection alone is not sufficient to present three-dimensional information on the two-dimensional screen, a grid representing a horizontal base plane and references lines indicating vertical separations from the base plane are also presented (Ellis et al., 1985; Kim et al., 1985 submitted). The human operator controlled the manipulator on the display using two joysticks to pick up each object with the manipulator gripper and place it in the corresponding box. One hand, using two axes of one joystick, controls the gripper position for the two axes parallel to the horizontal base plane (grid). The other hand, using one axis of the other joystick, controls the gripper position for the third axis (vertical height) perpendicular to the base plane. Picking up an object is accomplished by touching an object with the manipulator gripper. Likewise, placing an object is accomplished by touching the correct box with the manipulator gripper.

#### Puma Arm Simulator

In addition to the cylindrical manipulator simulation, the kinematics and dynamics of a six degree-of-freedom Puma robot arm were simulated. Each of these degrees of freedom were controlled simultaneously using two joysticks. Although no experiments have yet been performed with the puma simulation, it is hoped that it will be a step toward experiments with more complex manipulators. A low-bandwidth telephone connection to control two Puma arms at Jet Propulsion Labs in Pasadena is planned. The

simulation will allow prediction of the robots' motion to provide a preview display to help overcome the communication delays inherent in such a low bandwidth connection, or as in transmissions to manipulators in space.

## Helmet Mounted Display Design

### Motivation

The motivation of the HMD system is to provide the human operator with a telepresence feeling that he is actually in the remote site and controls the telemanipulator directly. The HMD system detects the human operator's head motion, and controls the remote stereo camera accordingly. In our current system, the remote telemanipulation task environment is simulated and the pictures for the display are generated by the computer.

### Head Orientation Sensors

A two-axis magnetic Helmholtz coil arrangement was used as a head orientation sensing device, to detect horizontal and vertical head rotations (Figure 3). By assuming that the pan and tilt angles of a remote stereo camera are controlled in accordance with the horizontal and vertical head rotations, respectively, the computer generates the corresponding stereo picture for the HMD. The head orientation sensing device is composed of a search (sensing) coil mounted on or beneath the helmet and two pairs of field coils fixed with respect to the human operator's control station. The right-left pair of the field coil

generates the horizontal magnetic flux of a 50 KHz square wave. The up-down pair of the field coil generates the vertical magnetic flux of a 75 KHz square wave. The search coil detects the induced magnetic flux, which is amplified and separated into 50 and 75 KHz components. The magnitude of each frequency component depends upon the orientation of the search coil with respect to the corresponding field coil (Duffy, 1985).

#### LCD Display

An early configuration of the HMD had a flat-panel LCD (liquid crystal display) screen (a commercially available portable LCD television) mounted on the helmet for the display (Figure 4). However, the picture quality of the LCD screen was poor due not only to low resolution but also to poor contrast.

#### CRT Display

A new design of the HMD that we currently have, mounted a pair of Sony viewfinders (Model VF-208) on the helmet (Figure 5). Each viewfinder has a 1-inch CRT (cathode ray tube) screen and a converging lense through which the human operator views the CRT screen. The computer-generated stereo picture pair (stereogram) is displayed on the CRT screens; one for the left eye and the other for the right. The converging lens forms the virtual image of the stereogram behind the actual display screen. When the CRT screen is 4.2 cm apart from the lens whose focal length is 5 cm, the virtual image of the CRT screen is formed at 25 cm apart from the lens with an image magnification of 6. Thus, a 1-inch CRT screen appears to be

a 6-inch screen to the viewer. At appropriate geometrical and optical conditions, the right and left images overlay, and most people can fuse the two images into a single three-dimensional image. The stereoscopic display formulas used to generate the stereogram for the helmet mounted display are described in references (Kim et al., 1987).

### Mechanical Design

Five degrees of freedom were provided for the mechanical adjustment of the position and orientation of each viewfinder, allowing three orthogonal slidings and two rotations (Figure 5). A 1 lb. counterweight was attached to the back of the helmet for counter-balancing.

### Communication Delay and Preview

Communication delay is a significant constraint in human performance in controlling a remote manipulator. It has been shown (Sheridan et al, 1964, Sheridan, 1966; Tomizuka and Whitney, 1976) that preview information can be used to improve performance. Stark et al. (1987) demonstrated that preview can significantly reduce error in tracking experiments with imposed delay.

Experiments were performed to investigate whether a preview display could improve performance in pick-and-place tasks with delay. A single bright diamond-shaped cursor was added to the display to represent current joystick position. This was a perfect prediction of what the end effector position would be after the delay interval. Thus, the task was the same

as if there were no delay, except that the HO had to wait one delay period for confirmation that a target had been touched or correctly placed (in the non-previewed display, the target letter was doubled when picked up, and became single again when placed in the correct box).

Preview improved performance at delays up to 4 seconds so that it was almost as good as for a small delay of 0.2 seconds (Figure 6). While task completion time in the delayed condition increased greatly with delay, there was only a small increase in the preview case. This is because the H.O. must compensate for delays by using a "move-and-wait" strategy, making a joystick movement and waiting to see the resultant and effector movement. In the preview case, this strategy is only necessary when very close to the target or box to wait for confirmation that the goal has indeed been touched.

#### Control Mode Experiments

Position and rate controls are the two common manual control modes for controlling telemanipulators with joysticks (or hand controllers) (Johnsen and Corliss, 1971; Heer, 1973). In the position control the joystick command indicates the desired end effector position of the manipulator, whereas in the rate control the joystick command indicates the desired end effector velocity.

In our three-axis pick-and-place tasks, the human operator controls the manipulator hand position in the robot base Cartesian coordinate by using three axes of the two displacement joysticks. In pure (or ideal)

position control, the system transfer function from the joystick displacement input to the actual manipulator hand position output is a constant gain  $G_p$  for each axis. In pure rate control, the system transfer function is a single integrator  $G_v/s$  for each axis. In the rate control, a 5% dead-band nonlinearity is introduced before the pure integrator in order to inhibit the drift problem associated with the pure integrator.

#### Comparison of Pure Position and Rate Controls

Three-axis pick-and-place tasks were performed with both pure position and rate control modes for various gains (Figure 7). The mean completion time plot clearly shows that pick-and-place performance with pure position control (mean completion time 2.8 seconds at  $G_p=2$ ) was about 1.5 times faster than that of the pure rate control (mean completion time 4.3 seconds at  $G_v=4$ ).

#### Trajectories of Joystick and Manipulator Movements

In order to examine why the position control performed better than the rate control, several trajectories of the joystick displacement input and the manipulator hand position output during the pick-and-place operation were observed. Typical trajectories from the start of trying to pick up an object to its accomplishment were plotted to illustrate position, rate, and acceleration controls (Figure 8). Components only for the x-axis (side-to-side) are plotted, since components for the other two axes are similar. Observation of several trajectories indicates that a precise

re-positioning of the manipulator hand is achieved by a combination of quick step re-positioning operations and slow smooth movement operations. In position control one quick step re-positioning of the manipulator hand from one position to another requires one joystick pull or push operation, whereas in the rate control it requires a pair of operations; pull-and-push or push-and-pull operations (Figure 8). This is a major reason why the position control yielded better performance than the rate control for our pick-and-place tasks. It should be noted, however, that the pick-and-place task is a positioning task. If the task is following a target with a constant velocity, then velocity (rate) control would perform better.

#### Acceleration Control

Three-axis pick-and-place tasks were also tried with acceleration control. It turned out, however, acceleration control was not adequate to perform stable, safe pick-and-place operations. In acceleration control, the manipulator tends to move almost all the time even though the joystick is at the center position. Note that in pure rate control, the manipulator does not move when the joystick is at the center position regardless of previous history of the joystick displacement.

#### Human Adaptation to Gain Change

Mean completion time did not change much for the various gains tested (Figure 7), which means that the human operator adapted well to the gain change (McRuer et al., 1965; Young, 1969; Stark, 1968). Both lower and

higher gains relative to the optimal gains caused slight increase in the mean completion time. A reason of slightly longer mean completion times with lower gains is because lower gains demand wider joystick displacements and it takes longer for the finger or hand to displace the joystick wider. A reason for slightly longer mean completion times with higher gains is that higher gains demand more minute joystick displacements, degrading effective resolution of the joystick control. An additional major reason for longer mean completion times with lower gains for the rate control is due to the velocity limit.

#### Force Joystick

The two common joystick types are the displacement and force joysticks. The output of the displacement joystick is proportional to the joystick displacement, whereas the output of the force joystick (isometric or stiff joystick) is proportional to the force applied by the human operator. The advantage of the force joystick is that it requires only minute joystick displacements (a few micrometers) in contrast with the displacement joystick (a few centimeters).

Pick-and-place tasks were performed for pure position and rate controls with displacement and force joysticks. The experimental results for two subjects (Figure 9) shows that in the rate control, task performance with force joystick was significantly faster than that with displacement joystick. This is mainly because the force joystick senses the applied force directly, requiring only very minute joystick displacements. In the position control, however, the force joystick

performed no better than the displacement joystick. In fact, all three subjects preferred to use the displacement joystick in this mode, since the force joystick required more force to be applied than the displacement joystick, especially when the manipulator hand is to be positioned far away from the initial center position. Position control also performed better than the rate control regardless of joystick types, and furthermore the position control with the displacement joystick performed best for our pick-and-place tasks (Figure 9).

#### Resolution

The experimental results demonstrate the superiority of position control when the telemanipulator has a sufficiently small work space (Figures 7, 8, & 9). Note that our three-axis pick-and-place tasks used in this experiment implicitly assumes that the manipulator work space is small or at least not very large, since our task allows the human operator to perform successful pick-and-place operations with a display showing the entire work space on the screen. Examples of small work space telemanipulators can be found in nuclear reactor teleoperators, surgical micro-telerobots, or small dexterous telerobotic hands. Position control can also be utilized during proximity operations in conjunction with the force-reflecting joysticks for enhanced telepresence (Bejczy, 1980). When the telemanipulator's work space is very large as compared to human operator's control space, position control of the entire work space suffers from poor resolution since human operator's control space must be greatly up-scaled to accommodate the telemanipulator's large work space (Flatau, 1973). One way of solving this poor resolution problem in

position control is using indexing (Johnson and Corliss, 1971; Argonne National Lab, 1967). In the indexed position control mode, the control stick gain is selected so that the full displacement range of the control stick can cover only a small portion of the manipulator work space, and large movements of the manipulator hand can be made by successive uses of an indexing trigger mounted on the control stick. Note, however, that rate control can inherently provide any higher degree of resolution by mere change of control stick gain without use of indexing.

#### Homeomorphic Controller

Most of our pick-and-place and tracking experiments were performed with joysticks as the input device through which the human operator controlled the simulated manipulator. The operator's movements when using joysticks are non-homeomorphic, so that the movements he must make to produce a desired manipulator response do not match the movement of the manipulator end effector. Thus, he must mentally convert the desired end effector position to Cartesian coordinates and use the joysticks to input these coordinates.

To attempt to study whether a truly homeomorphic input device could improve performance in tracking tasks, an apparatus of identical form to our simulated cylindrical manipulator was built. A vertical rod was supported by bearings on the base to allow rotation,  $\theta$ . A counterweighted horizontal arm was attached to the rod with sliding bearings to permit rotation and translation in the  $r$  and  $z$  axes respectively. The human operator could control position through a handle

on the end of the arm corresponding to the end effector of the simulated manipulator. Potentiometers measured movement in each axis to determine input  $r$ ,  $\theta$ , and  $z$ . The LSI-11/23 computer read these values through A/D channels and displayed the manipulator in the identical position.

Three-dimensional tracking experiments were performed with the homeomorphic controller and with joysticks for gains varying from 1 to 5 to compare performance (Figure 10). The results do not show a significant difference between the homeomorphic controller and joysticks over the range of gain values. Although the larger movements required for the homeomorphic controller, with greater inertia and friction than the joystick, may have limited performance, we believe that human adaptability minimizes its advantages.

#### Training by Optimal Control Example

A simplified simulation of the manned maneuvering unit, MMV, enabled study of training of human control performance (Jordan, 1985). Only three translatory degrees-of-freedom,  $x$ ,  $y$  and  $z$ , were used. Thrusters generating pulses of acceleratory control were controlled via a keyboard and the task was to accelerate simultaneously in  $x$ ,  $y$  and  $z$  to a maximum velocity, transit to the desired new location, and decelerate again simultaneously. Two displays were used -- a perspective display of a minified model of the MMV, or two two-dimensional projectors of that model with a small inset of the perspective display.

Subjects generally performed poorly during the few hundred seconds allowed for the tasks (upper panel, Figure 11). It was decided to allow the subjects to view this control problem carried out by a simple optimal control algorithm (see middle panel, Figure 11). This experience was of considerable help and several subjects then performed quite well (bottom panel, Figure 11).

This experiment, learning-by-example, illustrates a strategy that perhaps may be effective in more complex and realistic tasks as well.

INDUSTRIAL DRIVERS FOR CERTAIN NECESSARY  
SPACE STATION TECHNOLOGIES

**DRAFT**  
**NOT FOR DISTRIBUTION,**  
**ATTRIBUTION**  
**OR QUOTATION**

This next section deals with the future, and especially with "industrial drivers" other than NASA for new technologies which may be required in the evolving Space Station. In Table 5 I list nine components of a telerobotics system that certainly seem to be driven by important industrial hardware requirements, research and development. Therefore, it seems reasonable for NASA to sit back and wait for and evaluate these developments, saving its resources for those necessary technologies that will not be so driven.

Looking at these figures gives us some concept of how industrial development may provide various types of technologies for the evolving Space Station; indeed, NASA may be able to pick and choose from off-the-shelf items! For example, the most powerful computers on the last space shuttles were the hand-held portable computers that the astronauts

brought aboard which contained much greater capability than the on-board computers; those had been frozen in their design ten years ago in the planning stages for the space shuttle.

#### NECESSARY TELEROBOTICS TECHNOLOGIES TO BE SPARKED BY NASA

However, there are several areas in telerobotics that may likely not be driven independently of NASA, or where NASA may have an important role to play. Indeed, the Congress has specifically mandated that 10% of the Space Station budget should be used for Automation and Robotics development, and that this in some sense should spearhead industrial robotics in the United States (Table 6).

#### UNIVERSITY NASA RESEARCH

I now would like to make a plea that NASA should expand and stimulate telerobotics research conducted within the university environment. Of course, as a professor I may have a bias in this direction and I am willing to listen to contrary arguments! In addition to the benefits of the research accomplished by universities, NASA also gets the education and training of new engineering manpower specifically directed towards telerobotics, and focused on the evolving Space Station.

What kind of university and educational research should be funded in general by NASA. I believe there are two levels of cost (with however three directions) into which these educational research labs should be classified.

(i) First are Simulation Telerobotics Laboratories. Here we need graphics computers, perhaps joysticks, perhaps higher level supervisory control languages, cameras, image compression techniques and communication schemes. I would guess that our country needs at least thirty such systems for education and training. These systems should be very inexpensive, approximately \$50,000 each. They need not even be paid for by NASA, since universities can provide such research simulation laboratories out of their educational budgets or from small individual research grants. Our Telerobotics Unit at Berkeley has been thus funded. A good deal of exploratory research can be carried out inexpensively in this manner.

(ii) Second, we need Telerobotic Laboratories with physical manipulators present as important research components. In this way, experiments with various robotic manipulators, especially those with special control characteristics such as flexibility, homeomorphic form, new developments in graspers, and variable impedance control modes, other than are found in standard industrial manipulators, would be possible. I guess that there are about five such laboratories in some stage of development at major universities in the country. I would further estimate that these laboratories could each use an initial development budget of \$300,000 to enable them to purchase necessary hardware in addition to software as existent in the Simulated Telerobotics Laboratories.

Another set of costly laboratories would be Telerobotics Laboratories with remote operating vehicles (ROV). Here again, we need about five laboratories at universities with first class engineering schools. Again, I estimate about \$300,000 each for the initial hardware support of these ROV labs. They could then study transfer vehicles, local Space Station vehicles, Moon/Mars Rovers, and even compare MMU vs. telerobotic controlled vehicles.

The university laboratories would contrast with and serve a different function than ongoing aerospace industrial laboratories, and NASA and other government laboratories. These latter assemble hardware for demonstration and feasibility studies. Then unfortunately they are somehow unable to carry out careful human factors research dealing with the changing design of such pieces of equipment. In the university setting, this apparatus could be taken apart, changed, revitalized, modified and the flexibility would inform our current capability. I would like to contrast the Gossamer Condor and Gossamer Albatross with the NASA program. It was clear that if McCready was ever to be successful, he had to build an experimental plane which was expected to break down each experimental day. But the plane could be repaired in a few minutes! This "laboratory bench" concept is so different from twenty-year-ahead-planning currently controlling our space program that has been effectively eliminated at NASA. I think it is important to reintroduce rough and ready field laboratories back into the space program.

## NASA PRIZES

Another role that NASA might play is to offer demonstration contracts or, even better, prizes for accomplishment of specific tasks. Again I turn to the Kremer Prize; here a private individual donated prize money to be awarded to the first to build a man-powered aircraft conforming to certain carefully laid out specifications.

Communication channels for controlling remote vehicles and remote manipulators are already set up. Thus we could have prize contestants demonstrating at differing locations on earth at one "g"; next demonstrations using elements capable of operating in space, or even more stringently, of having that minimum mass capable of being lifted into space; and then we might have true shuttle and space station demonstrations.

## INTELLECTUAL PROBLEMS IN TR FOR THE SPACE STATION

Finally, I would like to leave you with the thought that the list of to-be-sparked-by-NASA problems in Table 6 contains many important intellectual problems facing the area of telerobotics. Although these areas are being approached in our research community at the present time, it may not be possible to foresee what novel kinds of challenges will face the evolving Space Station in twenty years. Even though I may not predict accurately, I certainly hope I am there in person to watch telerobotics playing a major role in operating the Space Station.

## SUMMARY

The telerobotic, TR, system is a simulated distant robot with vision and manipulator and/or mobility subsystems controlled by a human operator, H.O. The H.O. is informed mainly by a visual display, but also by other sensors and other sensory displays, i.e. auditory, force or tactile. His control can be direct via joysticks, or supervisory via command and control primitives effected by partially autonomous robotic functions. Delays and bandwidth limitations in communication are key problems, complicating display and control (Stark et al., 1987).

Class experiments enabled our Telerobotic Unit at the University of California, Berkeley to explore in a number of research directions. The HMD direction has now been greatly extended and is a major focus in our laboratory. On the other hand, the homeomorphic controller did not seem to be a productive project to continue because of the adaptability of the H.O. to many configurations of control. Also, our interest in supervisory and other high level controls is leading us away from the direct manual control. The students taking a graduate control course, ME 210 "Biological Control Systems: Telerobotics," during the fall semester, 1985, in which the helmet mounted display, HMD, is emphasized, were enthusiastic and felt the course stimulated their creativity and provided an opportunity for them to engage in relatively unstructured laboratory work -- a good model for subsequent thesis research.

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TABLE 1 Triplicate Planning

---

Problems with man alone

Hazardous environment:

(space similar to nuclear plants, underseas)

Expensive (i.e. EVA in space)

Need increased quality in

Strength

Fatigue resistance

Vigilance

Performance

Problems with Autonomous Robots

Not yet available

Design not fixed

Feasibility not certain

Reliability not tested

Therefore: TR is a viable leading edge technology

All three directions should be supported for evolving space station planning, research, and development.

---

TABLE 2 NASA should Hypothesize TASKS for Evolving Space Station

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Housekeeping

Life support systems

Inventory control, access and storage

Record keeping

Garbage disposal

Protection

From space garbage

From meteorites

From traffic flow

Maintenance

Satellite

Vehicles

Space station itself

Construction

Additional space station structures

Manufacturing

Crystal growth, biopharmaceuticals

Mobility

Automatic piloting

Navigation

Path planning

Scientific

Landsat type image processing for agriculture

Meteorology

Astronomy

Human factors research

Scientific record keeping

TABLE 3 Display Problems for the Human Operator

---

Display graphics (raster/vector)

On-the-screen enhancements

On-the-scene enhancements

Other senses displayed

Inputs to other senses

Perspective and Stereo Displays

Task performance criteria

Helmet Mounted Display

Telepresence; space constancy

Human Operator (H.O.) Performance

Fatigue, effort, vigilance

Robotic Vision

LLV - Chips

MLV - blockworld and hidden lines

HLV - ICM, AI

---

TABLE 4 Control and Communication Problems for the Human Operator

---

Basic properties of H.O., especially for EVA task performance

Nerve, muscle, AG/AT model

Sampled-data (SD) and adaptive control

Prediction, preview, optimal control -- Kalman filter

H.O. control of vehicles, manual control

H.O. control of TR

H.O. special control:

Preview, delay, bilateral, homeomorphic control

Locomotion (human, robotic):

Navigation -- pathways

Potential field algorithms

HLC (high level control):

Supervisory control

Multiperson cooperative control; RCCL; fuzzy sets

Autonomous robotic (AR) control

Sensory feedback, adaptive control, AI

---

TABLE 5 Drivers other than NASA for Nine Needed Technologies

---

Robotic Manipulator and Control Scheme

Joystick - Aircraft

AR Manufacturing Industry, Nuclear Industry, Mining Industry,

Sensors: Force and Touch; compliant control

ROV and Mobility

Military, tanks and other vehicle plans?

Undersea ROV - Oil and Communications Industry

Locomotion - University Research

Shipping Industry: Ships at Sea [AR, TR, Man]

TV Camera

Entertainment Industry - commercial device

Security Industry

Need mounts, controls and motors for PAN, TILT and for Stereo VG

## Graphics

Entertainment industry is a better driver than companies building

Flight Simulators;

- HMD as an example.

EM sensors research/Head-Eye Mouse

## ICM

Landsat

Security

Medical Industry - CT and MRI

Industrial Production Lines

TD - Image Understanding

## Computer

Computer Industry

(HDW) and (SFW)

Computer Science research base is now very broad

Communication

Communication Industry is huge

Ships at Sea

BW Compression

Remote Oil Rigs

Arctic Stations

Plans and Protocols to Combat H.O. Fatigue and to Promote H.O. Vigilance

Office Automation Forces

Air Traffic Control Needs

Security Industry

Cooperative Control

Military - submarine control

Helicopter flight control

Air traffic controllers

Nuclear industry

Chemical plant industry

TABLE 6 Areas Sparked by NASA not Industrially Driven

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Visual Enhancements for Graphic Display

Telepresence with Stereo Helmet Mounted Display (HMD)

Multisensory Input Ports:

Worry about H.O. overload condition

(especially with cooperative control and communication)

Higher Level Robotic Vision:

Example -- Image Compression by Modeling (ICM)

(to require less information flow and faster update)

## Special Control Modes for H.O.

Homeomorphic control

Bilateral control

Time delay and preview control for time delay

Compliant control

## Higher Level Control Languages

(such as ROCL; fuzzy control; path planning by potential field construction)

## Remote operating vehicles (ROV) special control problems:

Navigation, orientation, obstacle avoidance for ROV

## Cooperative Control:

Cooperation amongst humans, telerobots, and autonomous robots

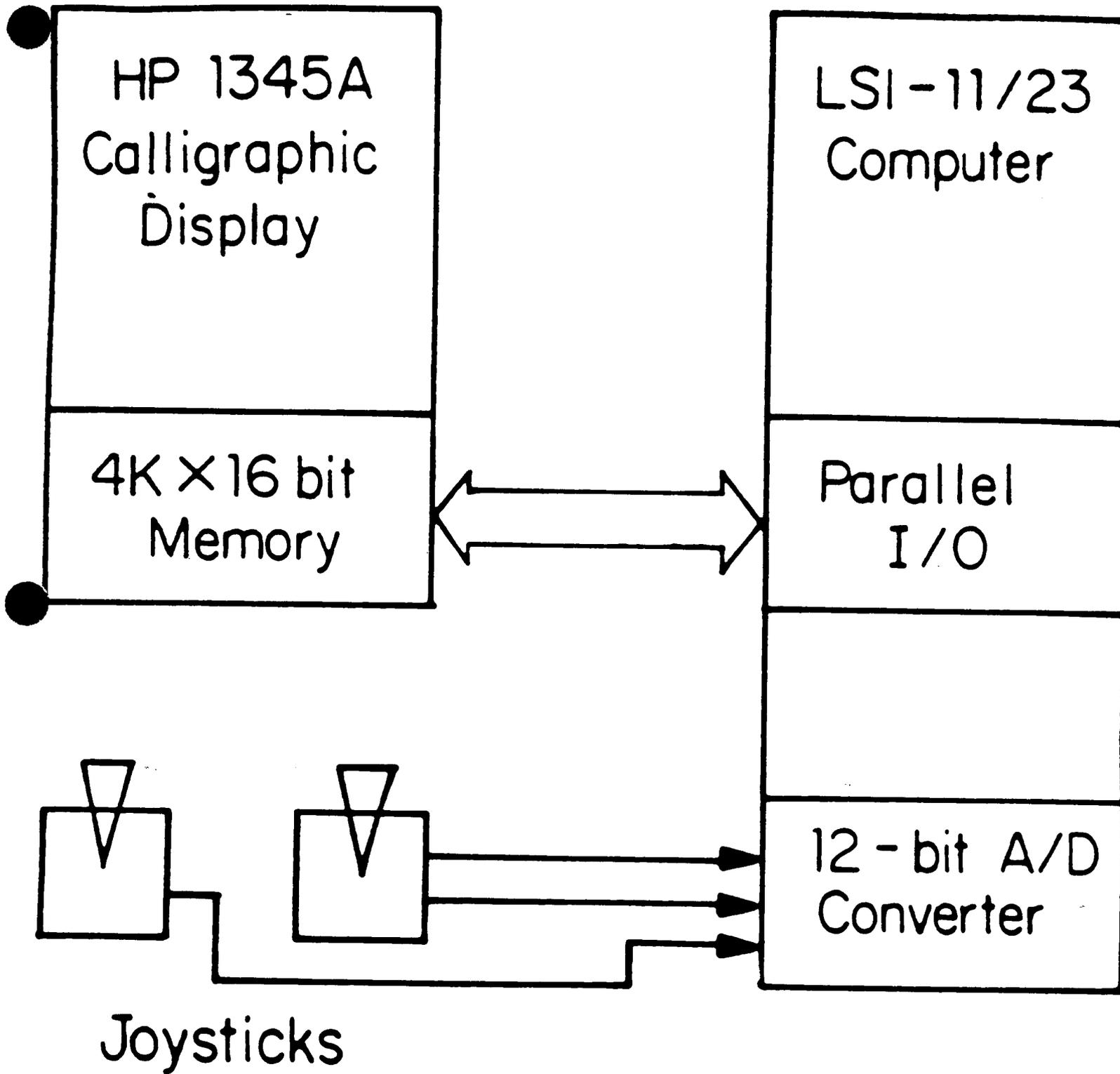
Compliant, Flexible, Homeomorphic Manipulators

Grasp versus tool using

Homeomorphic Dual Mode Control

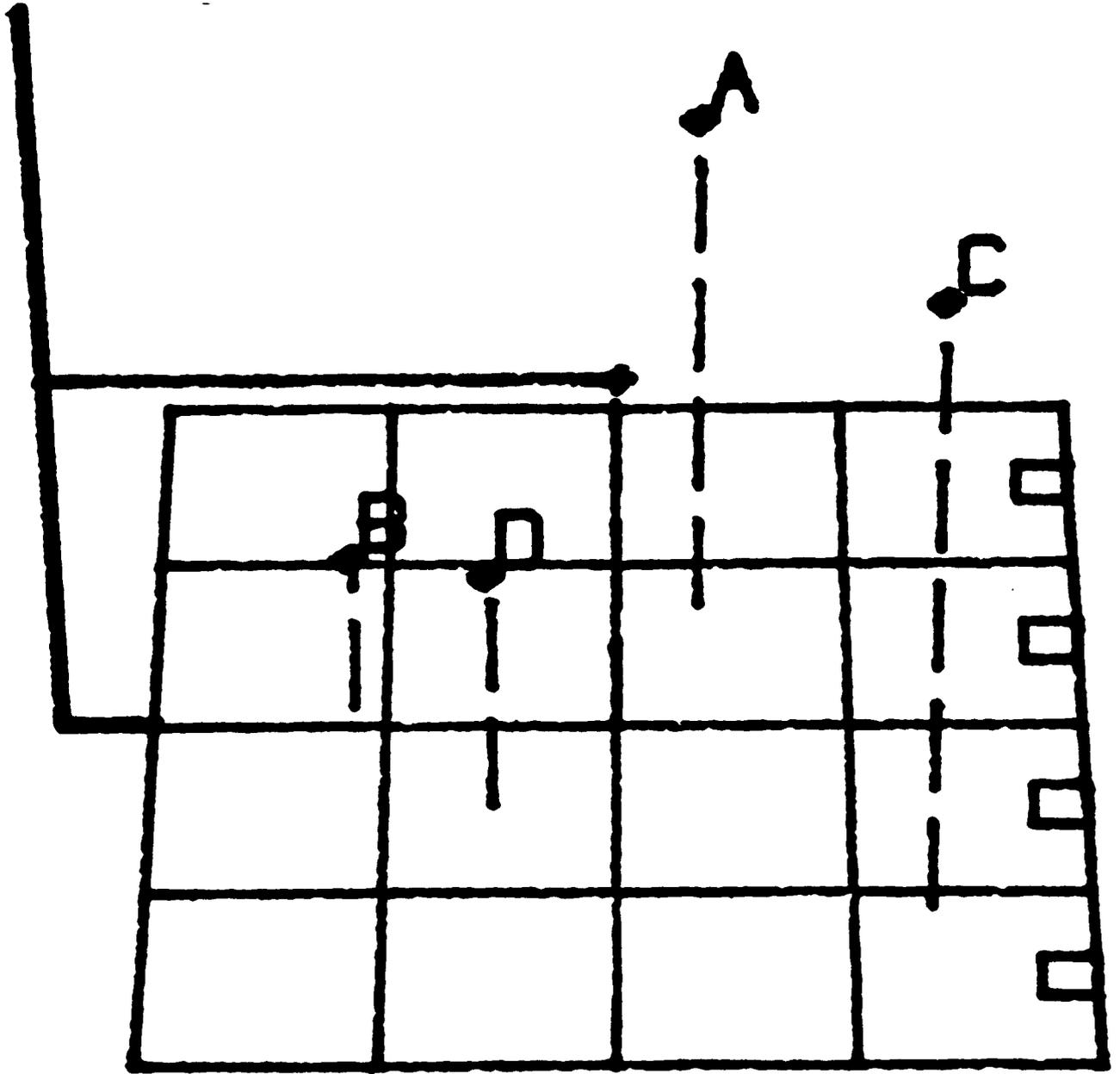
Impedance Control

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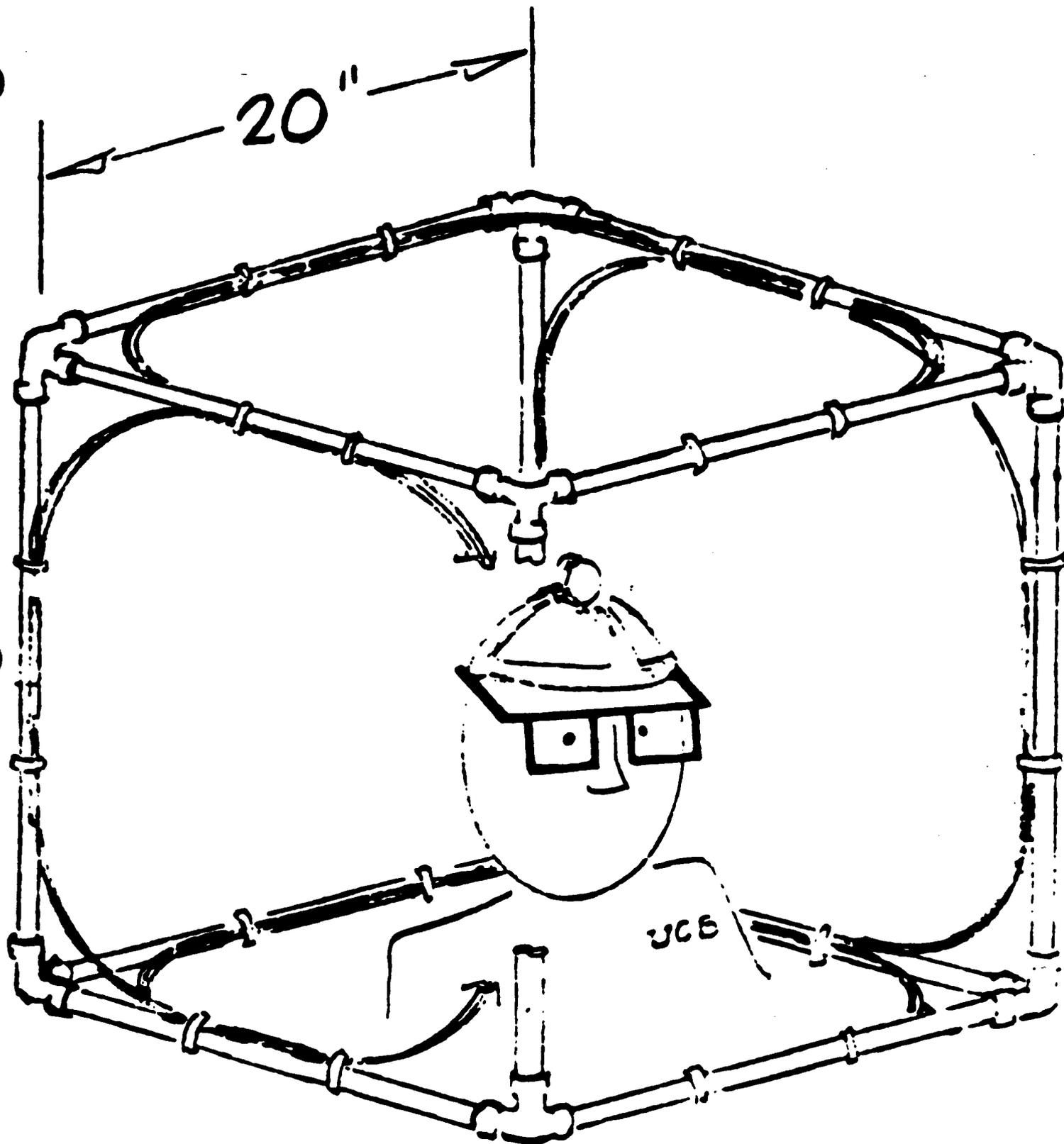
Joysticks

FIGURE 1  
EXPERIMENTAL  
ARRANGEMENT



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FIGURE 2  
AMES-BERKELEY VISUAL  
ENHANCEMENT DISPLAY



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FIGURE 3  
HEAD ORIENTATION  
SENSOR DEVICE

LIGHT SOURCE

SUPPORT CHANNELS

LCD DISPLAY

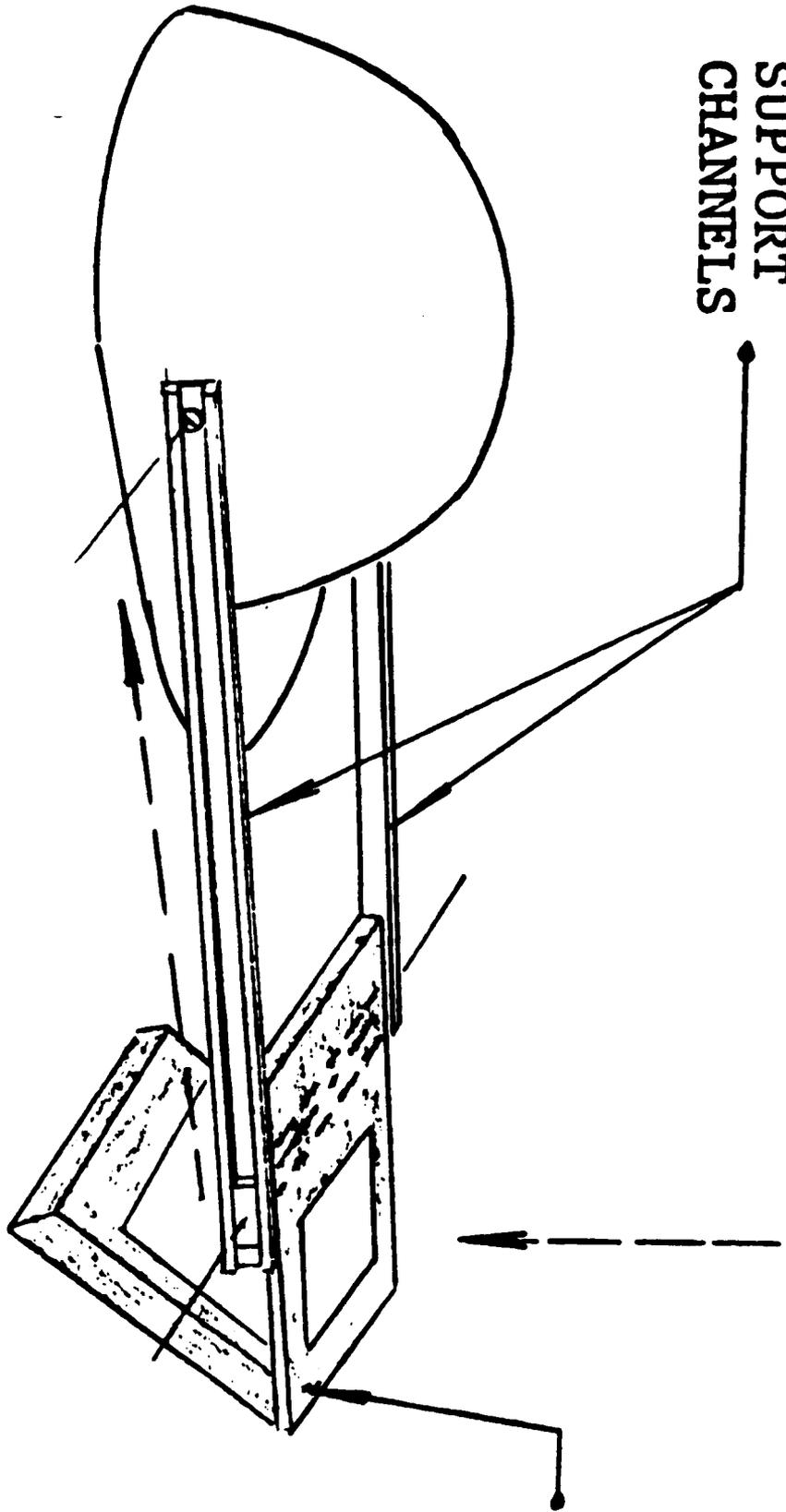


FIGURE 4  
EARLY HUD DESIGN  
WITH LCD SCREEN

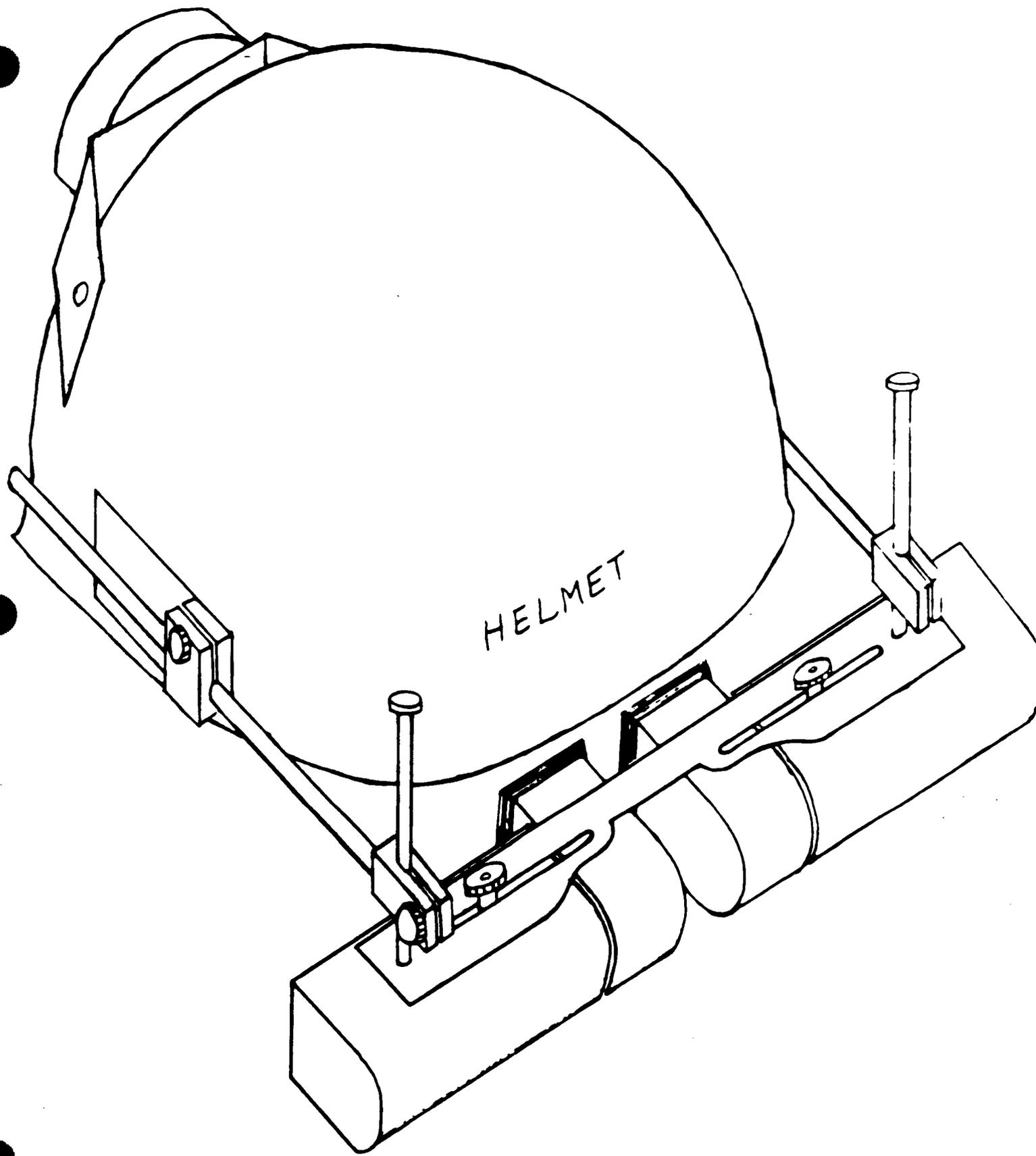
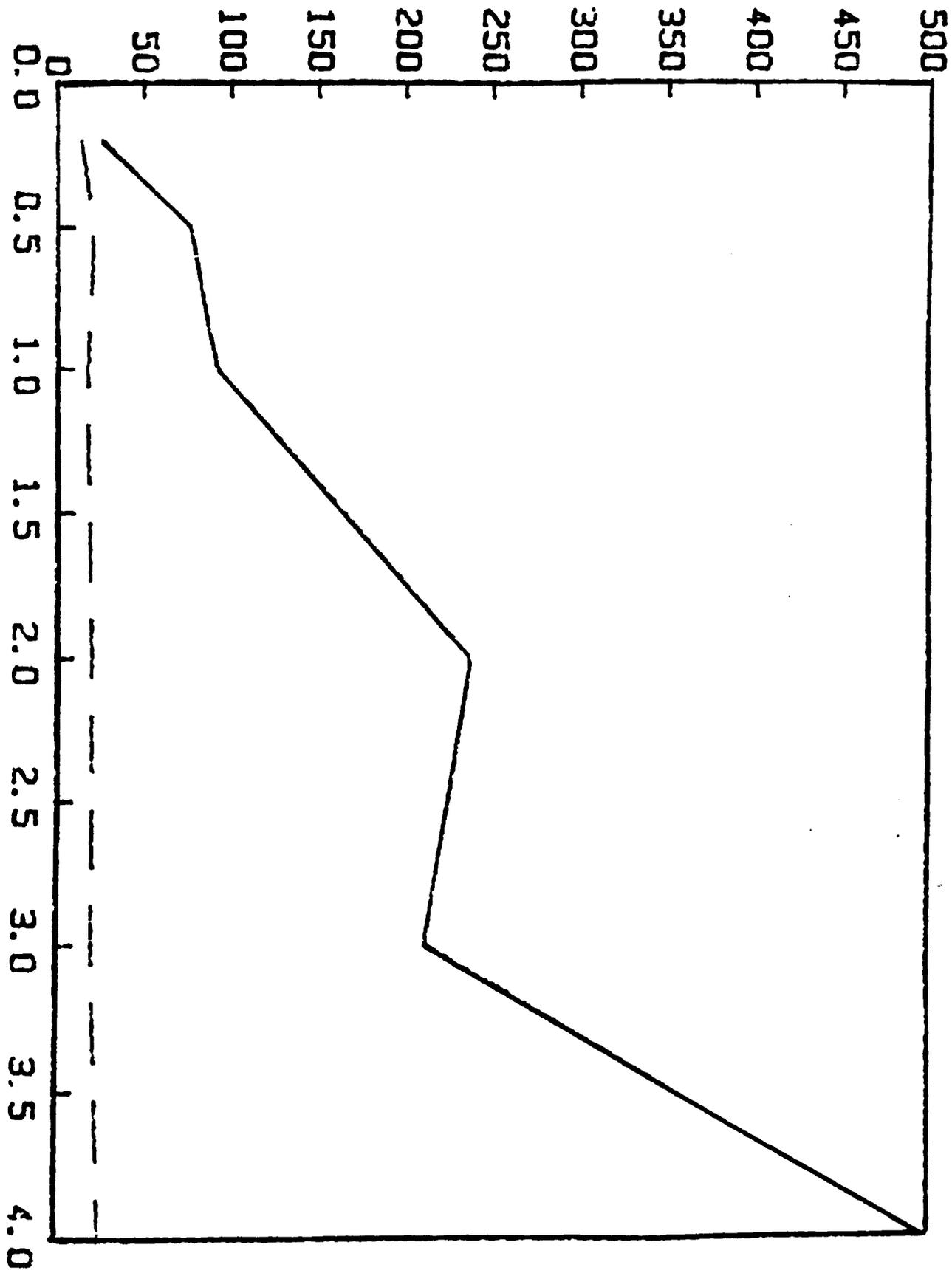


FIGURE 5  
CURRENT HMD DESIGN

Mean Completion Time (seconds)



Delay Time (seconds)

Figure 6  
PERFORMANCE AFFECTED  
BY DELAYS AND BY  
REVIEW CONTROL MODE

STARK

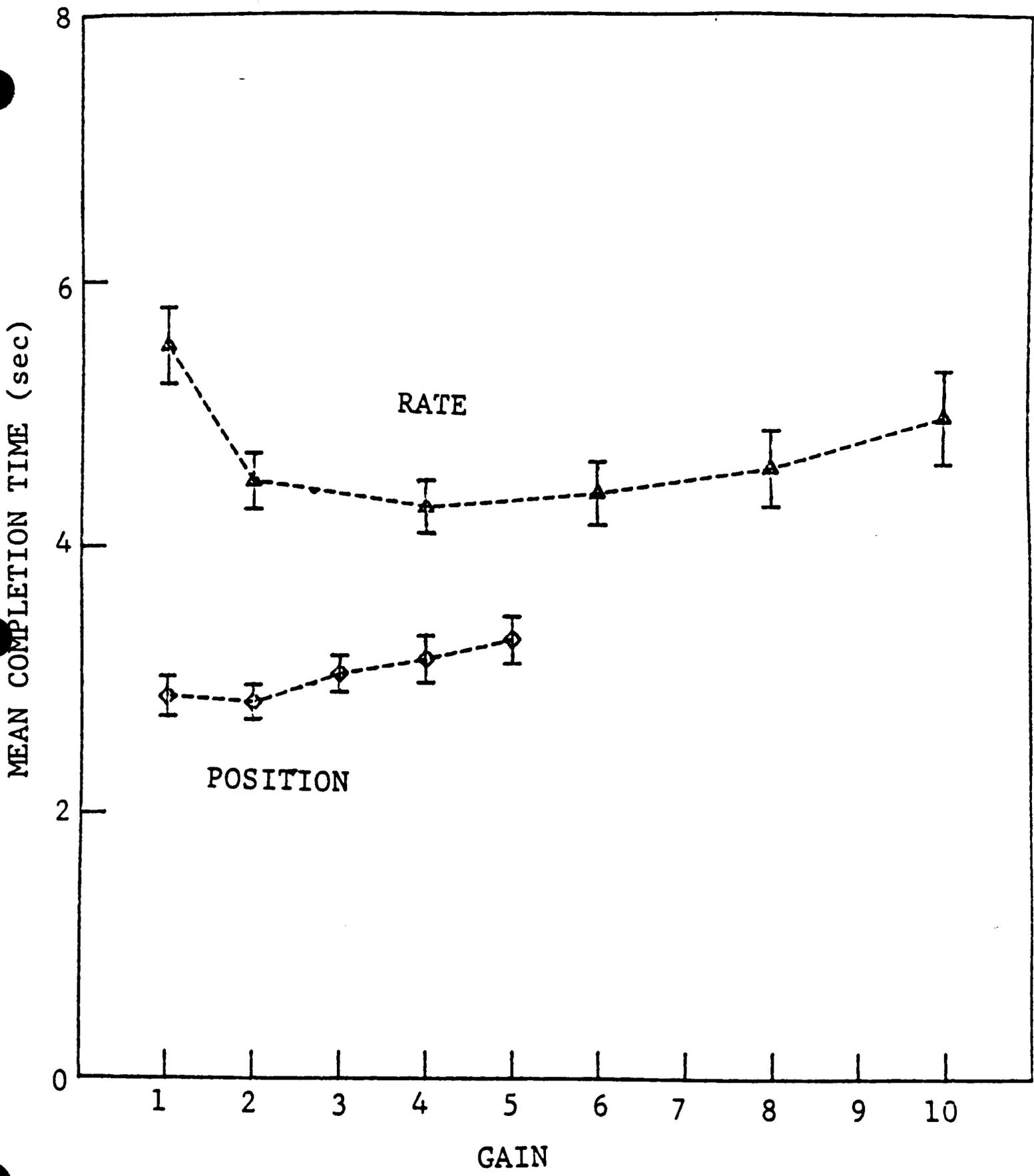
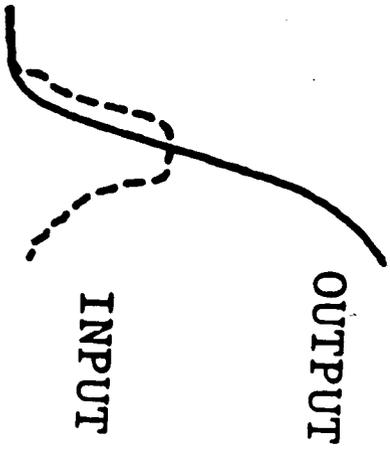


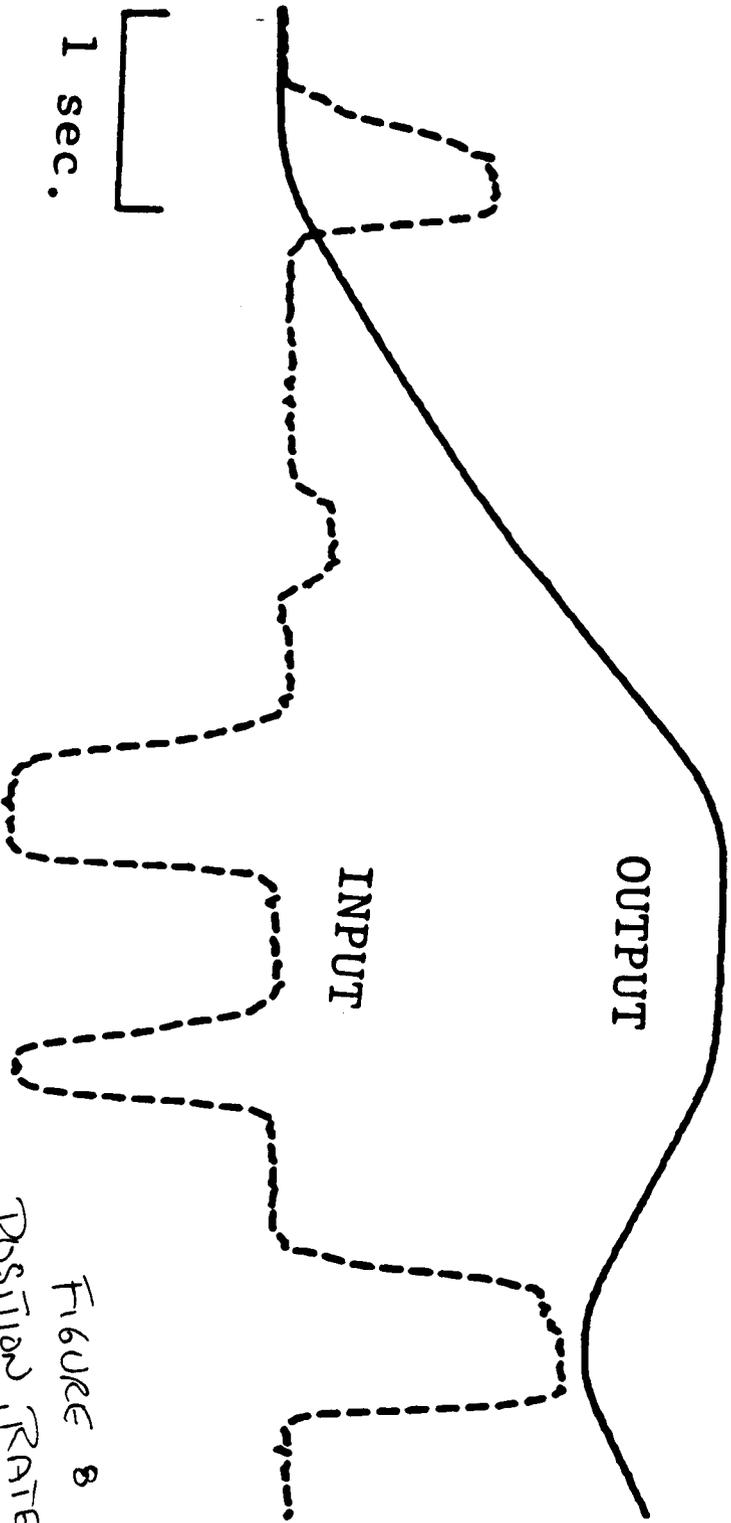
FIGURE 7  
PERFORMANCE COMPARISON  
OF POSITION AND RATE  
CONTROL



POSITION CONTROL

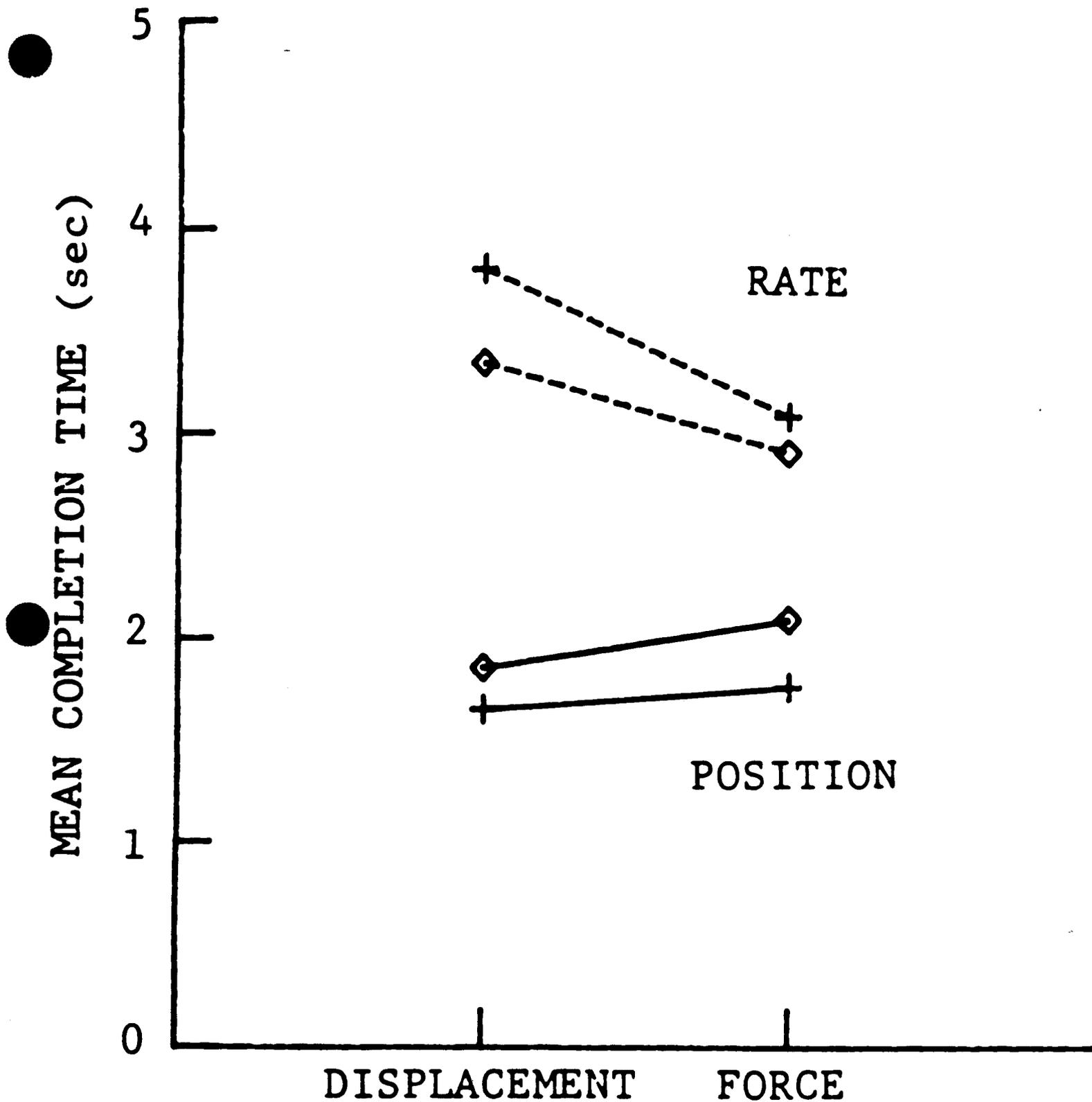


RATE CONTROL



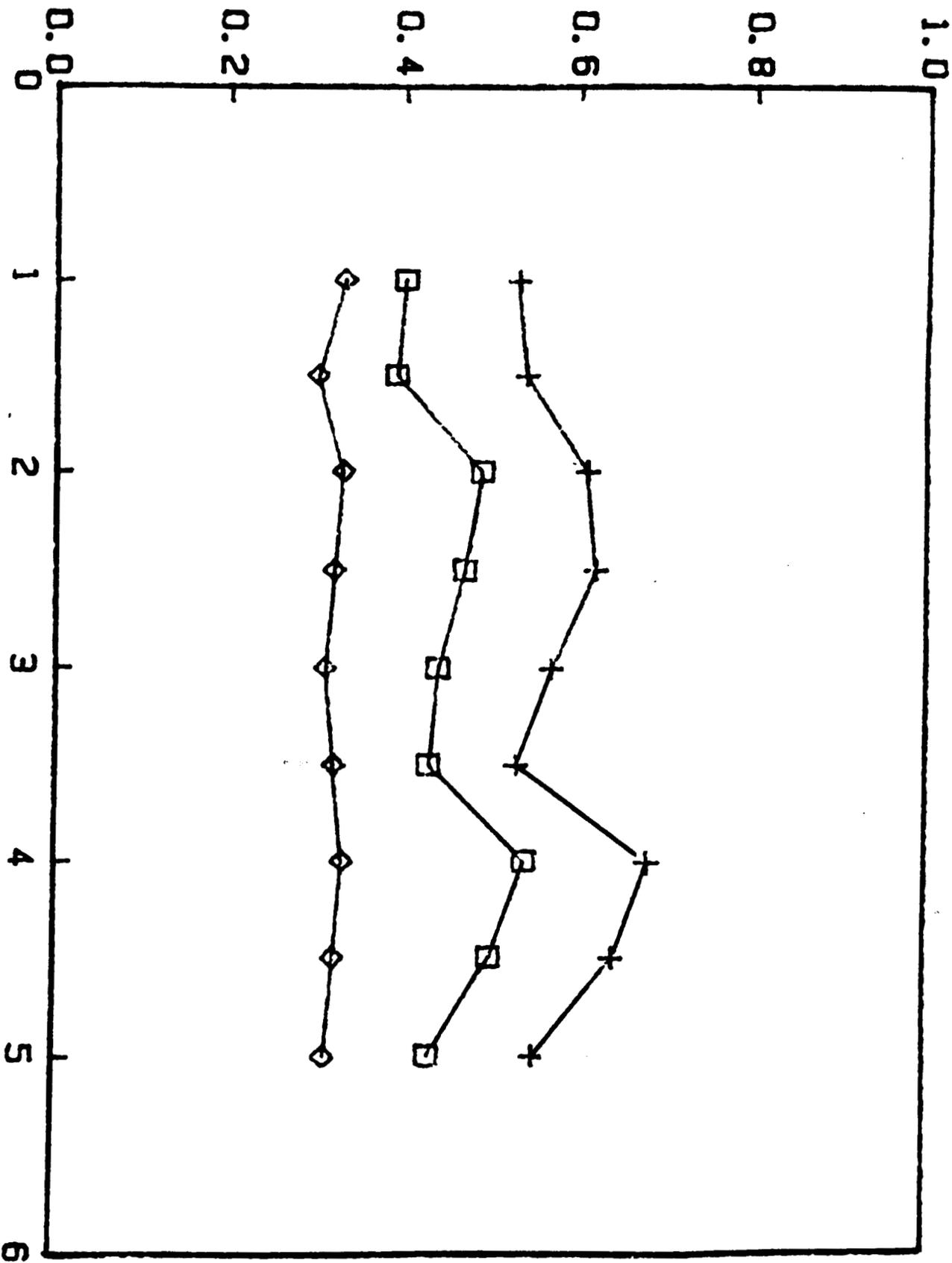
ACCELERATION CONTROL

Figure 8  
Position Rate and  
Acceleration Control



JOYSTICK TYPE *FIGURE 9*  
*DISPLACEMENT AND*  
*FORCE JOYSTICK CONTROL*

# RMS Error



Vertical Gain

FIGURE 10  
HOWEADPHIC CONTROLLER

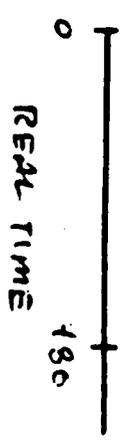
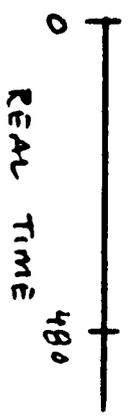
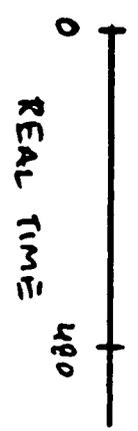
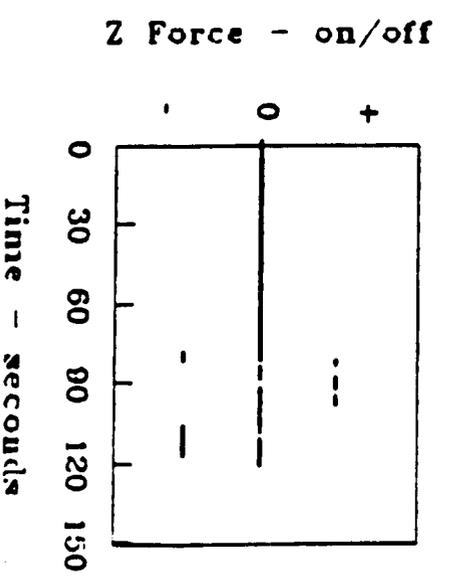
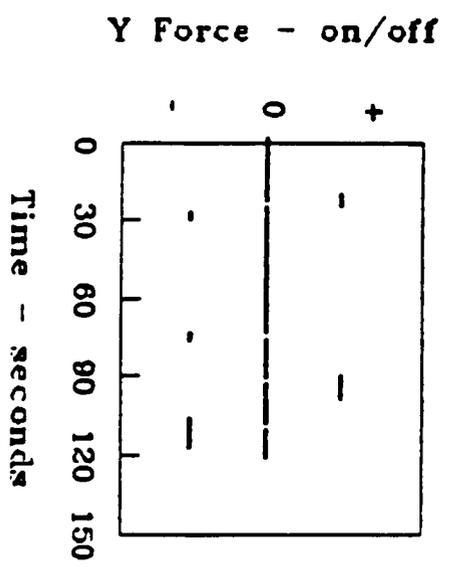
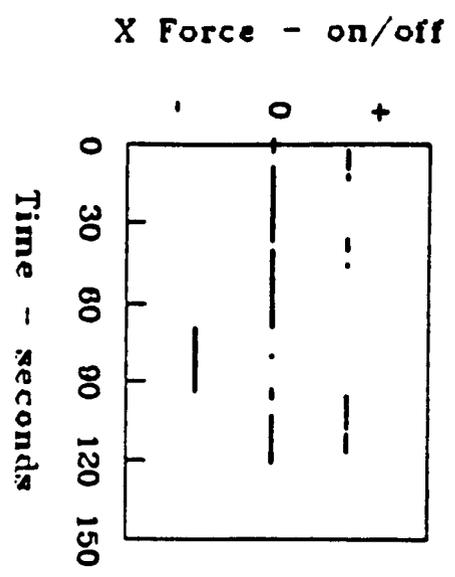
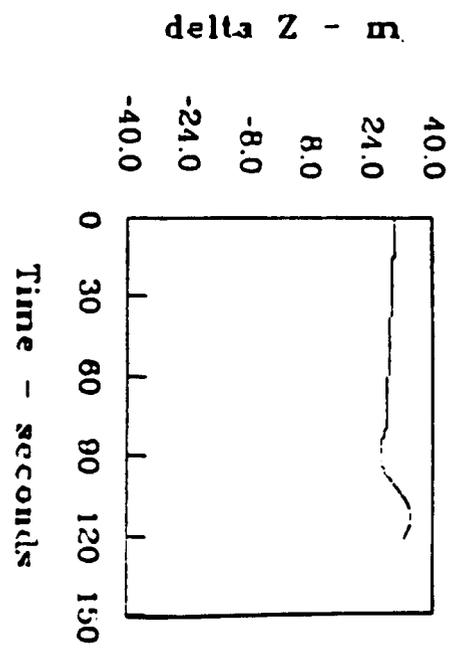
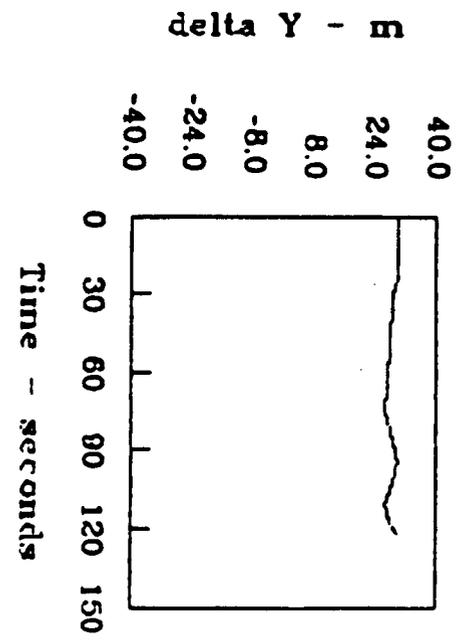
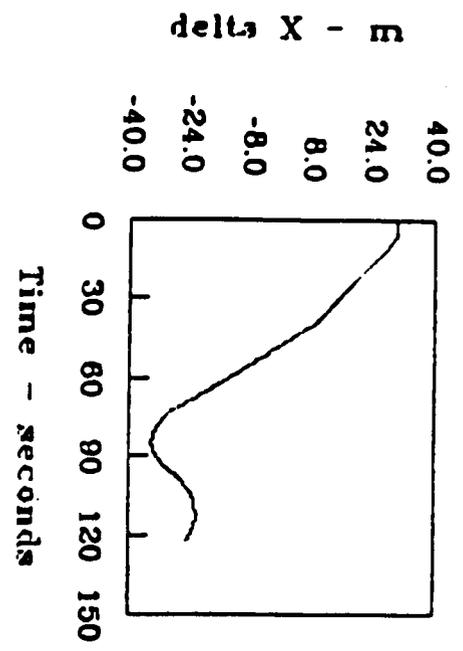
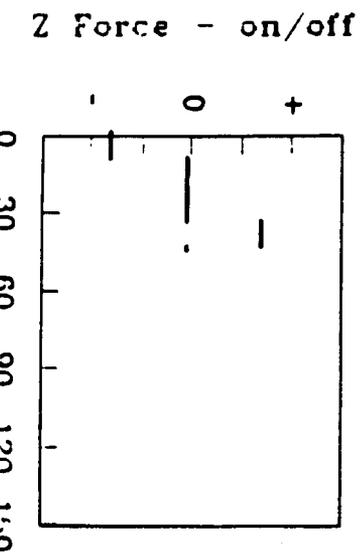
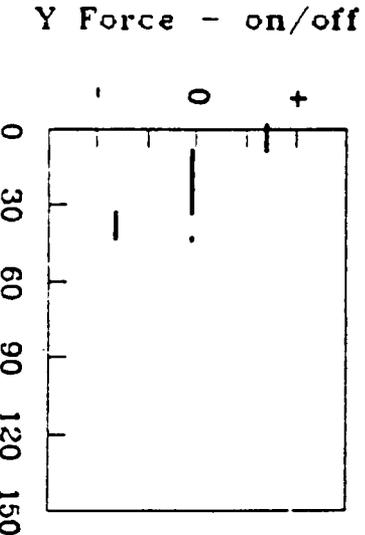
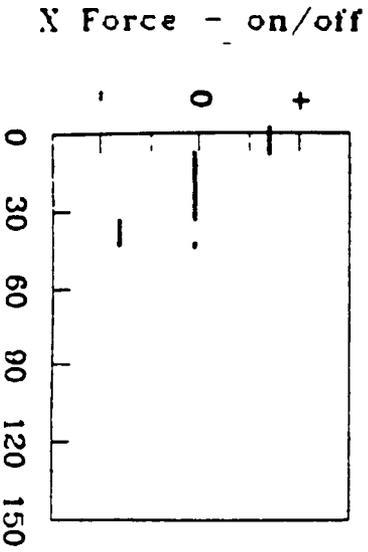
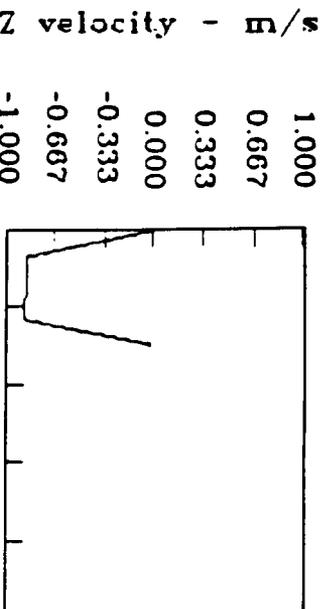
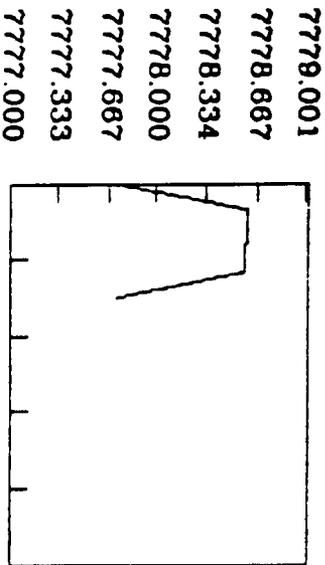
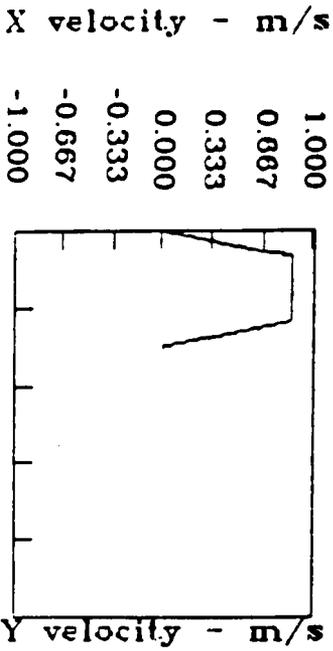
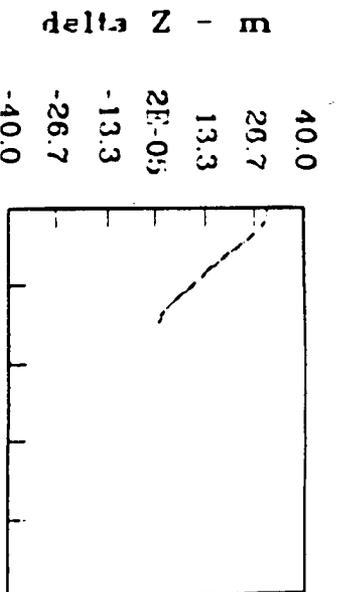
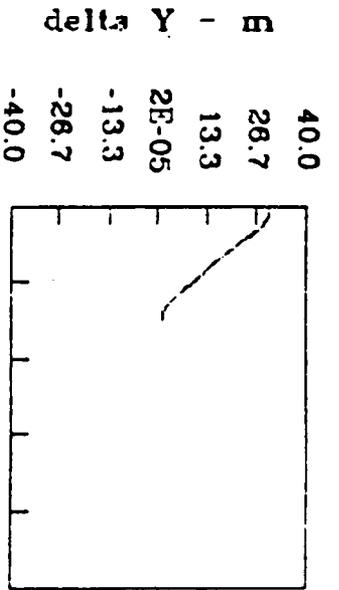
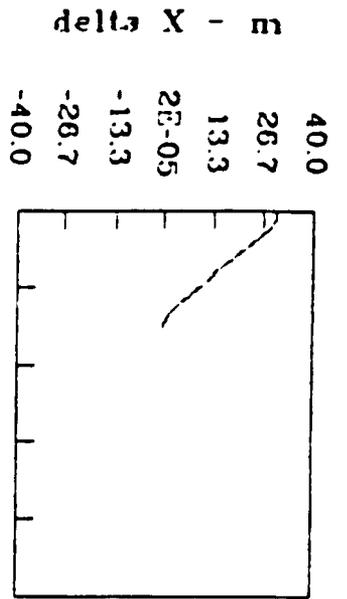


FIGURE 11  
 TRAINING BY EXAMPLE  
 (HUMAN OPERATOR CONTROL  
 BEFORE AUTOMATIC)



Training EXAMPLE

(Automatic Control Repts)

FIGURE 12

Time - seconds

Time - seconds

Time - seconds

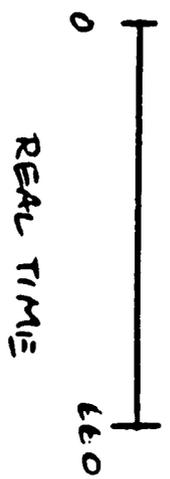
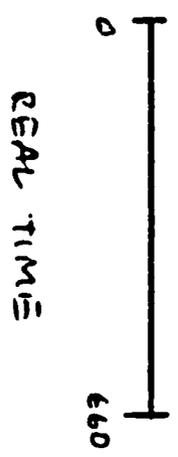
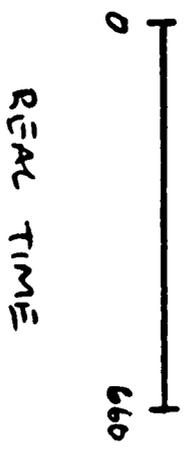
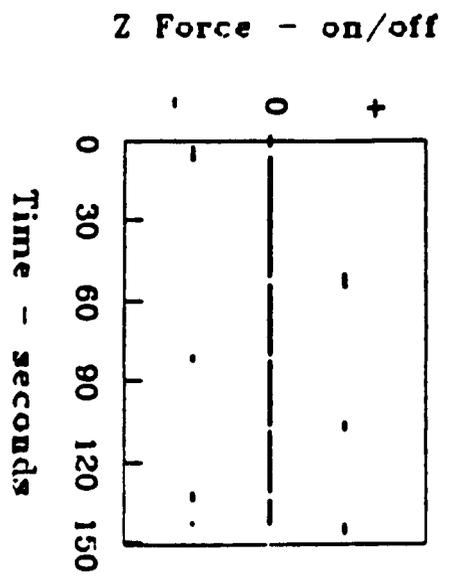
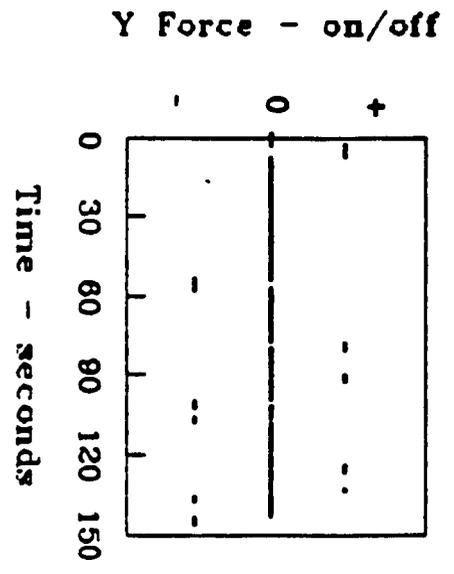
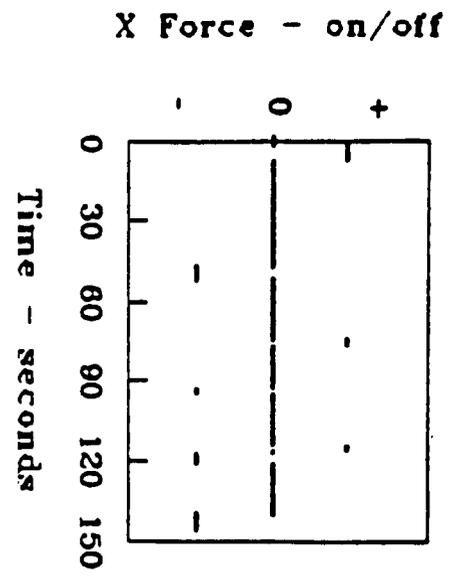
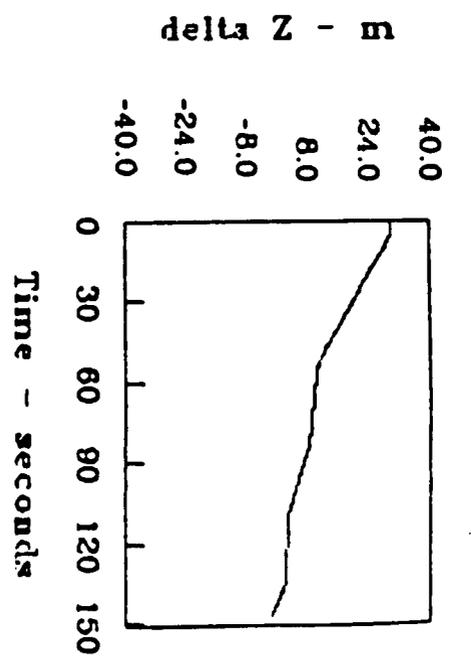
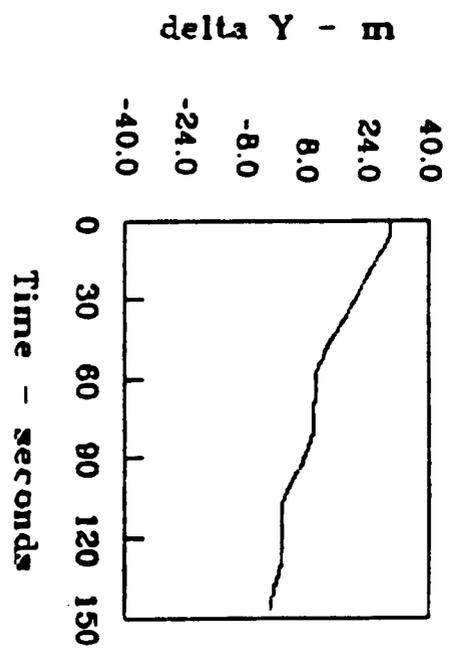
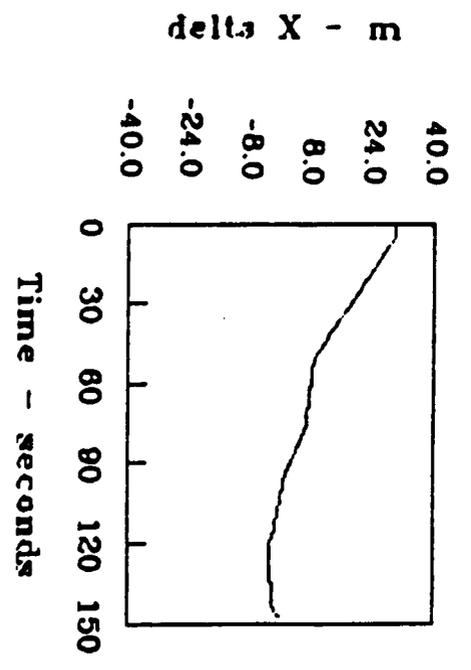


FIGURE 13  
 TRAINING BY EXAMPLE  
 (HUMAN OPERATOR CONTROL  
 AFTER AUTOMATIC)

TELEPRESENCE AND SUPERVISORY CONTROL

A COMMENTARY ON THE SHERIDAN AND STARK PAPERS

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Antal K. Bejczy

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

## TELEPRESENCE AND SUPERVISORY CONTROL

### A COMMENTARY ON THE SHERIDAN AND STARK PAPERS

Telepresence and supervisory control technologies, as Professor Sheridan pointed it out, represent advancements or refinements of existing teleoperator technology capabilities. Both technologies are strongly driven by and rely upon increased computer and computing capabilities and are regarded as substantial contributors to evolving space station capabilities in the sense of reducing EVA astronaut involvement in assembly, servicing and maintenance operations. Moreover, both technologies carry the promise of substantial spin-off for advancing capabilities of the U.S. production and service industries.

Professor Sheridan and Professor Stark enumerated and elucidated many specific topics and issues in sensing, controls and displays for telepresence and supervisory control which need research attention to advance the state of the art in the two technologies. In my discussion and comments, I would like to focus attention on the same research topics and issues from the following viewpoints: (a) In what sense and to what extent can we expect the enhancement of human operator capabilities through telepresence and supervisory control? (b) What specific conditions and constraints are imposed by the space application environment on the evolving telepresence and supervisory control technologies? (c) The multidisciplinary nature of the required research effort since neither telepresence nor supervisory control are intrinsically separate science or engineering disciplines. A brief description of the basic objectives of

telepresence and supervisory control technologies may help illuminate the questions that arise from the above three viewpoints.

The basic objective of telepresence technology is to alleviate the human operator's sense of remoteness in the control station by providing sufficient information to the operator on the activities of the remote machine in usable form. The content of the last attribute "usable form" heavily depends on human capabilities under given conditions, on the capabilities and characteristics of machines to be controlled, and on the nature of tasks to be accomplished. Also implied in this technology is the operator's enhanced control response ability to the perceived remote events. Briefly, telepresence technology is aimed at providing -- so to speak -- a more intimate, sensitive and high fidelity input and output connection between operator and remote machine.

The basic objective of supervisory control technology is to provide sufficient capabilities for the human operator to tell the remote machine what to do and, eventually, how to do it, without involving the operator in continuous control coordination of a multitude of machine actuators needed to execute a task (note that a dual-arm system contains fourteen or more actuators). Thus, in supervisory mode of control, the operator controls the task instead of controlling the individual degrees of freedom and associated actuators of a multi-degree-of-freedom complex machine. Implied in this technology are two important technical capabilities: (a) flexible automation of actions of a multi-degree-of-freedom complex mechanical system, and (b) flexible language-like or menu-type interface to, or interaction with, the automated mechanical actions of a remote machine.

Several notes should be added to the objective descriptions of telepresence and supervisory control technologies. First, none of them eliminates the human operator from the operation, but both change the operator's function assignments and employ human capabilities in new ways. Second, both technologies promise the performance of more tasks with better results, but, in doing so, both technologies also make a close reference to human capabilities of operators who will use evolving new devices and techniques in the control station. Third, both telepresence and supervisory control technologies make reference to evolving capabilities of other technologies like sensing, high performance computer graphics, new electro-mechanical devices, computer-based flexible automation, expert systems for planning and error recovery, and so on. Thus, the progress in both technologies are tied to rich multidisciplinary activities. Fourth, both technologies require the evaluation and validation of their results relative to the application environment. For space station scenarios, this implies the effect of zero-g on human operators, restricted local resources (like power, work volume, etc.) for a control station in Earth orbit, limited communication bandwidth and some communication time delay between a control station and remote machines, fragile and sensitive nature of space systems a teleoperator machine will be working on, changes in visual conditions in Earth orbit relative to visual conditions on Earth, and so on.

The above notes, together with the objective description of telepresence and supervisory control technologies, motivate a few important conclusions.

First, the high fidelity, human operator referenced, man-machine coupling -- hardly worked on in telepresence technology -- suggests we revisit anthropomorphic machine technology. The primary reason for the revisit is not a declaration of some intrinsic optimality of anthropomorphic machines, but a recognition of their potentially easy and natural interface to human operators to physically extend the rich human manipulative capabilities, embodied in the dexterity of the human hand, to remote places. One may visualize a backdrivable glove-type device on the operator's hand connected through bilateral control to a controllable mechanical replica of the human hand equipped with some sensing capabilities. This vision may not seem too strange when capabilities of component technologies needed for the development of this anthropomorphic machine are considered.

Second, the performance of nonrepetitive, singular or unexpected teleoperator tasks in space may benefit from the development of shared manual and automatic computer control techniques whenever application scenarios permit their use. These techniques intend to combine the best attributes of human operators and computer control under restricted conditions.

Third, the operator is facing a very rich environment in the control station in terms of decision, command, control and information processing even with increased telepresence and supervisory control capabilities. Due to the nature and time scale of activities in telemanipulation, the operator's mental status and readiness can be compared to an airplane

pilot's functional situation during take-off or landing. Thus, proliferation of control and information hardware in the control station does not serve the best interest of the human operator. The more computer technology is employed at the control and information interface in the control station in a clever way, the better off is the human operator to make control decisions efficiently.

Fourth, the R&D effort for advancing telepresence and supervisory control technologies should be accompanied by systematic work on developing a human factors data base and models for understanding and utilizing the results of these evolving technologies. It is apparent from the nature of these evolving technologies that the limits or limitations rest not so much with the technologies themselves but with the human capabilities to absorb and use these technologies.

Fifth, final evaluation and validation of telepresence and supervisory control technologies for space station naturally require experiments and manifests in space whenever human perception, decision, control and other activities are influenced by space conditions. Simulations are useful research and development tools, and they can pave the way towards performance evaluation and validation. But a comprehensive simulation of true space conditions on Earth for developing a human factors data base and models in telepresence and supervisory control technologies does not seem feasible.

Professor Stark make a strong case for NASA-University research in this arena. The benefits of NASA-University connections in human factors

research in the field of telepresence and supervisory control can indeed be manifested through past and present examples. Particularly appealing are cases when graduate students carry out the experimental part of their thesis research at NASA-supported, unique laboratories like ARC, JPL, JSC, and so on, or when students spend some working time at NASA laboratories as cooperative students or as academic part-time employees working on topics related to their university studies.

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SESSION 5:

TELEPRESENCE & SUPERVISORY CONTROL

SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

Antal K. Bejczy

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TELEPRESENCE & SUPERVISORY CONTROL  
SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

QUESTIONS AND ANSWERS

The first question was focussed on a comment, made by Professor Larry Stark, that wide-field-of-view displays are particularly needed in flight simulators. The question was prefaced with the suggestion that this is a limiting technology for anyone who is interested in robotics applications in space, where (a) the location of the observer is likely to be moving, and (b) the observer needs to be concerned, not only about the orientation of the object being manipulated, but also about his or her own orientation with respect to some larger coordinate range. It was noted that there are some state-of-the-art wide field of view displays that cost millions of dollars and proposed that some kind of research to lower the cost of wide-field-of-view displays might be in order at this point in time.

Professor Stark replied that, in this opinion, wide-field-of-view technology is very important. He provided the following example:

- o When people lose their wide field-of-view (e.g., have tunnel vision due to some neurological disease) they find that they can read and their visual acuity is 20-20; they find, however, that it is hard for them to merely walk through a doorway because they are lacking a functional flow-field, the lateral and vertical expansion flow-fields, which are directly connected by primitive neuro-pathways to the vestibular system and are coordinated in the

foculous of the cerebellum as shown in some brilliant studies by Jerry Simpson and other neurophysiologists recently; the lateral and vertical expansion flow-fields give us our orientation.

- o On the other hand, when people lose their foveal vision while retaining their flow fields, they are legally blind (with a vision rating of 20/200); they may not be able to read, however, they can still walk through rooms, get into a car, and drive (patients say -- "You know, Doctor, I can drive very well, I just can't read the freeway signs, so I don't know when to get off").

Professor Stark concluded that, when people are doing some tasks (manipulating, inspecting) they need foveal vision. In other cases (moving about within an area) they may need a wide-field-of-view. The human visual system is a dual system -- we have both -- and it should be possible to design something (perhaps using inexpensive TV cameras) to provide wide-field-of-view for gross movement tasks, and high resolution (like reading glasses) for manipulation tasks.

The second question was directed at Professors Sheridan's comment that there is yet no good way of describing (or representing) the process of manipulation. It was suggested that something like the notation system used by choreographers, to represent complex dance motions, might be useful in this context.

Professor Sheridan agreed that "labanotation" (dance scoring) or musical scoring (which is more thoroughly developed), is the kind of thing

that might be useful -- given a substantial amount of additional development. One problem discussed in relation to the use of this type of notation, was the fact that, for a given instrument, the range of manipulations (speed or fingering) is fairly constrained.

In teleoperations and robotics manipulations, the notation system would have to be able to cope with continuous geometry, hyperspace, and time. In this type of manipulation, considerations include: multiple degrees of freedom (six degrees of freedom for any object, plus maybe the six derivatives, plus the six accelerations -- and that is just the beginning) and multiple objects/components in motion (when three or four things are moving in relation to one another you immediately get into a twelve or twenty-four dimensional space and problems of dealing with trajectory in state-space to describe a manipulation). It is a very big order to develop a notational scheme which is both sufficiently complex, and sufficiently comprehensible, to be useful.

Professor Newell noted that the problem of telepresence (generating a feeling, on the part of a remote operator, of "being there" at the work site) is an interesting example of a situation where researchers are working with only a seat-of-the-pants notion of the underlying concepts. He suggested an immense need for a theory and a plausible model of presence -- a theory of what happens to humans (and why) when they "project" themselves to a remote work site.

Professor Sheridan suggested caution in the use of terms like "project oneself". He noted that it might be possible to project oneself

through drugs, or some other method, which would not be particularly helpful in terms of performance. In addition, he suggested that "being in control of" a remote operation might not require a feeling of "being there" -- that telepresence by itself is not the goal -- it is really performance that makes the difference.

These caveats notwithstanding, Professor Sheridan agreed that the development of a cognitive theory of presence would be a highly desirable goal. He suggested that "pieces of it are lying around" (e.g., the work of Murray and others in image rotation, etc.).

Professor Stark suggested that "teleprojection" is a very natural phenomenon. He noted, for example, that when an athlete swings a baseball bat, that he or she as an operator/tool user is able to "project" kinesthetically and visually to the end of the bat. He pointed out that people automatically develop models for activities that they do on a regular basis (e.g., picking up a pen, using tweezers), and suggested that persons operating remote equipment (e.g., a robotic arm 200 miles away) would develop the same sorts of models -- as long as there is some sort of causal relationship between their behaviors and the behavior of the remote system.

## CONCLUDING REMARKS

In conclusion, one should note that telepresence and supervisory control are not mutually exclusive. Telepresence is needed in supervisory control. The supervisory control language, for example, represents only one abstract operator output interface to the remote system. The perceptive element in supervisory control, that is, the information input to the operator from the remote system, should be in the form of telepresence "frames" in order to help the operator to determine the necessary abstract commands.

We should also note that telepresence has both qualitative and quantitative aspects. The qualitative aspects of telepresence are useful for stabilizing a control situation. The quantitative aspects of telepresence are not well understood (as indicated by control experiments). For instance, when I am working in a force field, and I have active force feedback to my hand, then I am stable -- but I have a poor quantitative perception of the acting forces. However, if I show the values of the acting forces on a display simultaneously with the active force feedback to my hand, then I am stable and reasonably good quantitatively. This type of cross modal reference should also be considered in creating telepresence capabilities.

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SESSION 6:

SOCIAL FACTORS IN PRODUCTIVITY & PERFORMANCE

Paper: Karen Cook, University of Washington

Paper: H. Andrew Michener, University of Wisconsin

Discussant: Oscar Grusky, University of California

SOCIAL STRESS, COMPUTER-MEDIATED COMMUNICATION SYSTEMS,  
AND HUMAN PRODUCTIVITY IN SPACE STATIONS:  
A RESEARCH AGENDA

Karen S. Cook

Department of Sociology  
University of Washington

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Multiple Stressors in Space

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INTRODUCTION

The sheer complexity of the space station program is enough to boggle the mind of any academic trained in a single discipline. Certainly, space station design requires the ultimate in interdisciplinary teamwork and integration of basic and applied programs of research. In this sense, the project demands knowledge and insights not easily produced in an isolated discipline, be it engineering, aeronautics or sociology. It is a challenging task and one that should call forth the best efforts of those touched by the allure of extending the boundaries of human knowledge.

For a sociologist there are a myriad of research problems which come to mind in even a cursory glance into the window of the future as envisioned by those currently planning the space station program. Clearly, a wide range of processes and factors must be taken into account when considering the more social aspects of this enterprise. These include technological constraints, environmental pressures, physiological limits, psychological processes (including cognitive capacities and motivational factors), and the many interfaces between "man" and machine required by the intense interdependencies of human and technological forces in space. Such intense interdependencies in this extreme are much less often observed on earth (with the possible exception of certain medical contexts in which life is tenuously maintained by sheer technological support).

Given this reality, one cannot extrapolate easily from what is known about society as we experience it on earth and "life aloft." It has even been said that humans may become a very different species while in space. Similarly, social systems which emerge to support and maintain life in this context may deviate along many dimensions from those social structures and processes that are a part of our daily existence and often so "routine" that they are taken for granted. Nothing must be considered as "routine" in a novel environment. It must be said at the outset that what we transport from earth in the way of social, psychological and organizational adaptive mechanisms (e.g. norms, rules, shared expectations, roles, etc.) may prove much less functional than we envisioned given a completely altered social and technological environment. Because we have virtually no scientific evidence concerning the parameters of life after eighty-four days in space (that is, there is no U.S. experience to rely on), one is forced to engage in speculation and extrapolation despite the potential pitfalls.

My reading of the documents we have been supplied with concerning the space station program in the 1990's and beyond and my very limited exposure to NASA through a two-day symposium, lead me to several tentative conclusions regarding the most critical social contingencies (besides the issue of conflict addressed by Michener) confronting NASA as it plans for the extended duration existence of groups of individuals in space with limited opportunity for replacement or exit. These critical contingencies include the social and psychological management of stress (regardless of the nature of the stressors) and determination of the most efficient and

socially productive mechanisms for handling interpersonal communications (e.g. within the crew, between crews of different modules, and between the crew and the "ground," including family members and friends). The successful management of both stress and interpersonal communications is critical to individual and group-level performance, productivity and ultimately, "mission success." While there are many other issues which could be investigated profitably from a sociological perspective, time and space limit the scope of this first foray into life as currently envisioned on space stations.

#### STRESS, INDIVIDUAL PERFORMANCE AND GROUP PRODUCTIVITY

Stress has been identified as a contributing factor in the etiology of certain acute and chronic illnesses (e.g. ulcers, high blood pressure, heart attacks, nervous disturbances, etc.). It has been demonstrated to have consequences not only for the health status of individuals, but also for individual performance, decision-making and productivity. With respect to space-related research Foushee (1986) states that an important goal is "to understand and minimize the effects of acute and long-duration stresses on group functioning." Although there is enormous literature on the effects of stress on individuals, researchers have been slow to address the impact of stress on groups. Furthermore, the bulk of the existing research examines the physiologic and psychological consequences of stress. There is much less work on the antecedents of stress, in particular the stresses created by social factors (Pearlin, 1982). Another limitation to existing research is the tendency for investigators especially in experimental work to focus on single, isolated stressors.

This work is extremely important, but it does not inform us about the interactive and/or cumulative effects of multiple stressors.

### Defining and Measuring Stress

The most commonly cited definition of stress is Hans Selye's, "the nonspecific, that is, common, result of any demand upon the body, be the effect mental or somatic." In the tradition of research initiated by Selye (e.g. 1936, 1956, 1974) this "result" or reaction of the body to stress is referred to as the "general adaptation syndrome" (GAS) or "biologic stress syndrome." It consists of an alarm reaction biologically detectable in such organs as the adrenal glands, thymus, lymph nodes and stomach, followed by the stage of resistance accompanied also by marked physiologic responses, then the stage of exhaustion at which point Selye argues the acquired second-stage adaptation is lost.

Other researchers emphasize the significance of the "cognitive appraisal" of stressors (see Breznitz and Goldberger, 1982, etc.), noting the importance of the "subjective, phenomenological experience of stress" which lies between the stressor and its effects. Some definitions of stress include reference to cognitive appraisal, others, like Selye's, do not. Currently, there is no agreed upon definition of the term and existing differences reflect major unresolved theoretical debates in the field. Though they disagree on the significance of cognitive appraisal, researchers do agree on the common goal of understanding adaptations to stress or the nature of coping mechanisms. Much of the current research focuses upon specifying the nature of these mechanisms. Before discussing

adaptations however, let us examine the problems associated with the measurement of stress.

Various approaches have been adopted to the problem of measuring stress; none of them completely satisfactory. One of the most common approaches to measurement, popular over the past two decades because it can be applied outside experimental settings, is the "life-events" scale (e.g. Holmes and Rahe, 1967) or the modified life-events scale (Dohrenwend and Dohrenwend, 1974a, 1974b). Life-events typically mean "objective events that disrupt or threaten to disrupt the individual's usual activities" (see Dohrenwend and Dohrenwend, 1974b:133, 1984). Events listed on such scales include both health-related (onset of chronic illness, major illness or accident, etc.) and non health-related events such as divorce, separation, increase in family income, retirement, death of a spouse, pregnancy or remarriage, etc. (see Thoits, 1981, for a cogent critique of the life-events approach).

The main debate in this research tradition has been over whether or not only undesirable events contribute to stress or whether events that require change either desirable or undesirable produce stress. The latter has been referred to as the "total change" approach to measuring stress, the former, the "undesirability" approach (Thoits, 1981). Thoits (1981) identifies several studies suggesting that only the undesirable changes significantly affect stress levels, although she goes on to critique these studies as well as many of the total change studies for failing to include independent indicators of their independent and dependent variables. Her findings also suggest that "when health-related events are controlled,

other undesirable events have small and nonsignificant effects upon psychophysiological distress" (as measured by reports of psychosomatic symptoms using the MacMillan Health Opinion Survey Index). The main conclusion she draws relevant to current research is that "previously well-established correlations between undesirable events and distress may have been inflated due to the operational confounding of health-related items on the independent and dependent variable scales." A major contribution of new research on stress would be to refine existing measures of stress and to develop more sensitive and reliable measurement techniques.

Laboratory research employs quite different methodologies than survey research, however, as Holroyd and Lazarus (1982:26) point out, "lab paradigms in biological science have tended to isolate stress responses from the psychological and social context." Though measurement problems are reduced in this way, little knowledge is gained concerning the interplay of physiological, psychological and social mechanisms. Holroyd and Lazarus (1982:30) call for "field research that examines stress in the psychosocial context" and more descriptive work on the sources of stress "that operate in naturalistic settings." The space station environment is a "natural" laboratory for this type of research.

#### Multiple Stressors in Space

The reality of space station existence includes the potential for continual and intermittent exposure to multiple stressors. In this regard it is not at all clear that much of the existing research, except that

done in analogous environments, can be extrapolated to apply to the space station. Both the number and the magnitude of stressors in the space environment is likely to be at the high end of existing scales, and quite possibly off the scale. Only research in rare, high stress situations will contain insights of direct relevance.

Sources of potential stress in space stations include sensory deprivation, environmental factors like noise level, crowding, spatial arrangements, and invasion of privacy, as well as isolation, confinement, and the possibility of life-threatening dangers or crisis situations. Nickerson in his chapter for this volume includes in the category of potential stressors: weightlessness, unfamiliar motion, motion restriction, sensory and perceptual restriction as well as sleep interference and acute medical problems. Work-related factors like variety and intensity of assigned tasks, and workload, etc. may also be stressors in the space station environment. Cooper (1983) indicates that in many work environments work or job overload is a major stressor. There is some indication that workload intensity and time pressure were factors that contributed to the problems experienced by crew members aboard the Skylab 4 Mission. According to Holroyd and Lazarus (1982:24), "the individual who is constantly challenged by even relatively innocuous occupational and social demands and who is, as a result, repeatedly mobilized for struggle may be particularly vulnerable to certain disorders (Glass, 1977)." Given the duration of planned space station missions, the cumulative physiological, psychological and social impact of intermittent and continual exposure to multiple stressors must be investigated.

Another significant factor in space stations related to multiple stressors is the recognition that the stressors will be produced by quite different types of events and forces. Stressors may be produced both by the astronaut's home environment, to the extent that s/he has information about significant events occurring on earth (e.g. in the lives of his/her close relatives and friends, etc.), and by life aloft. Within the space capsule, factors contributing to stress are environmentally induced resulting in both physiological and/or psychological distress as well as socially induced, created by factors associated with the interpersonal environment, especially the intense interdependence of the crew members. Since both physiological and psychological factors have been given more consideration in the existing literature, I will emphasize the social forces likely to induce stress.

#### Identifying Socially Produced Stressors

Outside of the life-events tradition and research focusing upon occupational stress (e.g. Cooper and Payne, 1978), there have been few investigations of stress produced by interpersonal factors in small group settings (Levine and Scotch, 1970). Potential causes of stress in settings requiring intense interdependence among group members include basic personality conflicts, incompatibilities in interpersonal orientation and style, an inefficient or inequitable division of labor, a lack of perceived legitimacy concerning the allocation of leadership responsibilities or authority, the inequitable allocation of individual or collective rewards, lack of a clear definition of role or task responsibilities, uncertainty regarding the timing, coordination or

sequencing of related tasks especially when synchronization is a critical factor, and the arbitrary or inappropriate exercise of authority or influence (i.e. violating role prescriptions or norms concerning the use of private time). Many of these factors have been demonstrated to have significant impacts upon group functioning in non-stressful situations and may or may not be exacerbated in situations of high stress. Research on mountain-climbing teams indicates that under periods of high stress many of these problems become extremely salient and in some cases result in aborted attempts to reach the summit. Interpersonal conflicts appear to be a major problem for many expeditions especially when the goal of reaching the summit is highly valued by all and where there is a great deal of uncertainty about achieving the goal. Connors (1985:147) also notes that in simulation research, "members of isolated and confined groups who were incompatible showed increased stress, withdrawal, and territorial behavior."

Many of these potential stressors have not been examined in the context of group functioning primarily because the predominant model in this area of inquiry has been one of individual functioning. I will comment more upon the limitations of such a perspective in a subsequent section of the paper.

#### Monitoring Stress

Related to the problem of measuring stress and identifying the antecedents of stress is the problem of monitoring stress. Unobtrusive mechanisms for monitoring stress at both the individual (physiologic and

psychological) level and the group level need development, given the potential deleterious consequences of high levels of stress for individual and group functioning. An important byproduct of such monitoring is that it will give us some insight into the interactive and cumulative impact of various stressors. Furthermore, it will enable us to address issues still under debate regarding the extent to which the effects are linear, curvilinear, or approximate a step-function (or threshold function). It may also be the case that the effects of certain stressors are compensatory given that not all the effects are potentially negative. The positive impact of stress has been given little attention in the literature.

#### Personal Characteristics, Crew Composition and Stress

As several authors have suggested, the "right stuff" may be the "wrong stuff" when it comes to the selection of crew members who will not only have the necessary technical and professional skills, but will also have the psychological and social competencies required for the creation of effective interpersonal relations and relatively smooth group functioning on space station "missions." According to Biersner and Hogan (1984:495), veterans believe that "social compatibility is as important as technical skills for overall Antarctic adjustment" to isolation. Social competence will become even more critical as a basis for selection and training in the future as NASA envisions shorter training periods for some astronauts (e.g. teacher and congressmembers in space programs). The potential for commercial joint ventures with NASA not only increases crew heterogeneity, but also means that some space station members in the U.S. module will in

all likelihood not have the benefit of intense NASA training (and selection).

Intriguing research by Helmreich and his colleagues (e.g. Helmreich et al., 1980) on this basic topic suggests that at least one characteristic typically associated with the "right stuff" constellation of traits, interpersonal competitiveness, may be dysfunctional for producing smooth group functioning depending upon the mix of personnel and their traits in any particular crew. As Connors (1985:155) notes, Helmreich et al. (1980) "hypothesize that the combined interests of task accomplishment and social compatibility will be best served if crew members show a strong work and mastery orientation, but relatively little competitiveness."

#### Group Decision-Making Under Stress

Research of particular interest to NASA is the research on the relationship between stress and decision-making which indicates that the experience of stress generally interferes with psychological processes related to effective decision-making. Janis (1982), for example, reports the following reactions associated with stress during decision-making:

- (1) narrowing of attention span and range of perceived alternatives,
- (2) reduction in problem-solving capabilities,
- (3) oversight of long-term consequences,
- (4) inefficiency in information search,
- (5) premature closure, and

- (6) with intense fear, there is also temporary loss of perceptual acuity and perceptual-motor coordination (Duffy, 1962).

Evidence further suggests that accelerating time pressure increases the probability of these reactions, although clearly more research is needed on the temporal aspects of stress reactions as well as situation specific/individual difference interaction effects. (Individuals in certain situations are likely to respond differently both to stress and to the demands of the decision-making task.)

Janis (1982) also specifies five basic patterns of decision-making under stress. The first four patterns in the list represent "defective" patterns of response, the fifth is the term Janis uses for the most adaptive response pattern. Observed patterns of response under stress include:

- (1) unconflicted inertia
- (2) unconflicted change
- (3) defensive avoidance
- (4) hypervigilance, and
- (5) vigilance.

Of the four defective response patterns, hypervigilance is found to be the dominant reaction under conditions of high stress or near-panic. As Janis (1982:77) notes, "Excessive alertness to all signs of potential threat results in diffusion of attention...one of the main sources of cognitive inefficiency whenever someone becomes hypervigilant, and it

probably accounts for some of the failures to meet the criteria for effective decision-making." Results also suggest that other problems emerge in high stress situations. "Along with cognitive constriction there is a marked tendency toward stereotyped thinking in terms of oversimplified categories and reliance on oversimplified decision rules" (Janis, 1982:78). Two conditions appear to enhance the probability of hypervigilance occurring in stressful situations: unconflicted inertia (or the failure to react to early warnings) and defensive avoidance (e.g. procrastination). Additional factors identified by Janis as associated with the antecedents of hypervigilance are the lack of contact with family members or other support persons, lack of perceived control and lack of preparatory information about potential stressful events.

The prevention of "defective" patterns of response in threatening situations has focused in recent years upon several strategies including "benign preexposure to the threatening situation, stress inoculation via preparatory communications" and various types of relaxation techniques designed to mitigate physiologic reactions (Janis, 1982:82; see also, Janis et al., 1982). Research on these techniques and the extent to which they are successful under specific circumstances continues. Extrapolation to situations likely to be encountered in space stations must be done carefully. Some techniques may be effective for single stressors, but less effective in the face of multiple stressors. Again, further research is needed. Certainly, however, this research gives us some clues as to problems associated with decision-making in highly stressful contexts.

A Comment on the Limits of Medical and Psychological Models of Stress: The underlying framework a researcher adopts to the analysis of a problem often circumscribes both the nature of scientific inquiry as well as conceptions of potential solutions. Thus it is not surprising that medical research on stress tends to examine primarily physiologic response patterns and the impact of drugs on the functioning of the individual undergoing stress. Psychologists similarly focus on cognitive and emotional factors, examining individual differences associated with cognitive appraisals of stress and reactions. The solutions they consider include biofeedback, stress "inoculation", and various types of individual training and therapeutic techniques. All of this research is necessary since the problem entails both physiologic and psychological dimensions. What is missing, however, from much of the current work is the investigation of the system properties of stress and examination of solutions to the problems created by multiple stressors at the group or collective level (also sometimes called the system level). Inquiry of this type would examine the interpersonal dynamics related to stress responses and adaptive strategies rather than treating the problem purely from an intraindividual perspective. Adoption of an interpersonal or system level perspective would lead to quite different conceptions of adaptive mechanisms. In Connors (1985:146) words, "Given that future missions will require increased levels of cooperative functioning, selection and training procedures must not only yield effective individuals, they must yield effective groups."

The dominant characteristic of space station missions in the near future involving 6-8 crew members marooned in space for approximately

ninety day intervals of the high degree of interdependence among the group members (and possibly between groups in different modules at some point). Stressors which significantly impact any single group member will, of necessity, influence group functioning -- even if it simply entails the reassignment of duties or tasks for brief periods of time or temporary isolation of a group member. In addition, group members may be impacted similarly by stressors and thus collective solutions should be explored. Strategies might be developed, treating the group as a social system (as Michener does) of interdependent parts and group members might be trained in specific response patterns through a division of labor. For example, roles could be assigned such that each attends to a specific problem associated with inefficient decision-making under high stress. One crew member might be assigned the task of vigilance with respect to only alternatives, another to long-term consequences, etc. and coordination might be achieved either by an assigned group leader or some sort of computerized decision-aide.

Computer-aided systems could be developed which help to meliorate common deficiencies observed in cognitive processing during peak periods of stress. Coping strategies of this type are more like Janis' suggestion that an appointed "devil's advocate" be used to mitigate the negative consequences of "groupthink." They have the possible advantage that "failure" is not localized in a single individual (typically, the "leader") who must assume full responsibility for group decisions in "crisis" or intensely stressful situations. Furthermore, a clear division of labor also reduces the workload on any single individual under stress. The work on distributed decision-making by Fischhoff and others may

well provide models for this type of coping mechanism. Relevant work on computer-aided decision-making should also be explored.

#### Mediators of Stress and Adaptation

In the words of Holroyd and Lazarus (1982:25), "It has been increasingly acknowledged that health outcomes are a product of effective coping rather than simply a consequence of the presence or absence of stress." Identifying factors that result in effective coping is an important research agenda item, however current investigations focus more on drug therapy, biofeedback and "cognitive-behavioral" interventions to modify responses to stress and facilitate coping. The social and organizational management of stress, as noted above, has not been examined. Psychological approaches take us one step beyond physiologically focused management strategies, but even they have not been evaluated extensively.

Coping mechanisms and adaptation responses form one axis of current research, the second axis is extensive work on factors that "mediate" the stress response. Such factors include individual differences which relate not only to susceptibility, but also to cognitive appraisal and effective coping. Variables incorporated into these investigations are ethnicity, age, gender, occupation, income, level of education, marital status, health status and access to social support (i.e. personal resources and network supplied resources), among others. Access to social support, for example, has been demonstrated to mitigate some of the effects of stressful events (e.g. Caplan and Killilea, 1976). Much of this work is useful for general medical and scientific purposes, but caution must be

exercised when attempting to generalize these findings to astronauts and the space station environment. The range of variation on some of these variables is quite restricted in the astronaut population, although increasing heterogeneity must be assumed along many of these dimensions (i.e. gender, age and ethnicity) in the future.

Research linking gender to stress, for example, indicates in a variety of studies that women are more susceptible to stress (e.g. Kessler and McRae, 1981); given certain levels of stress they report higher levels of distress as reflected typically in symptomatology (primarily self-reports). Research discussed by Kessler and McLeod (1984) documents that women tend to be more affected by undesirable life events than men even though they do not report significantly more such events. Kessler and McLeod (1984) present findings that indicate that women are more vulnerable to "network" events, events that happen to significant others in their networks, than men, and it is this difference that accounts at least in part for previously observed sex differences in responses to stress. Thus, they argue that women are not "pervasively more vulnerable than men to stress," but vulnerable specifically to stress linked to the important people in their lives as a result of their "greater emotional involvement in the lives of those around them." Belle (1983) refers to this fact as the "stress of caring".

There are many unanswered questions concerning the link between gender and stress. The extent to which female astronauts are more vulnerable to stress than male astronauts is an open question. Few of the existing studies include in their samples women in such high stress occupations and

it may well be that women with high capacities for coping with stress self-select into these occupations (e.g. as is likely the case for women mountain climbers). It should also be noted that many of these studies reporting sex-related stress differences are based on sample data obtained in the 1950's, 1960's and early 1970's; little evidence exists based on more recent data including samples of women in more varied occupational contexts and roles.

#### Impact on Productivity: Individual and Group-Level Effects

The link between stress and productivity has been demonstrated to be somewhat complex. Mandler (1982:94) argues that "the problem of stress is twofold; both the initial autonomic signals and the conditions that generate these signals require some conscious capacity...and therefore interfere with the performance of targeted tasks." What is not clear is specifically how and under what conditions performance is impaired. In fact, as Mandler (1982:96) indicates, like noise, stress reduces "attentional capacity and narrows it to central tasks," thus if the target task is central, "then autonomous arousal may improve performance." This depends upon both the centrality of the target task and specific characteristics of the task, or task sequence which requires performance. Early research on this topic seemed to suggest that there is a curvilinear relationship between arousal and performance such that performance is enhanced by moderate levels of arousal, but impaired significantly at both very low and very high levels of arousal. The generality of this effect is still under debate. Mandler (1982:95) concludes that "understanding the relation between efficiency and stress requires an analysis of

specific stressors, an approach to arousal that assigns it definable properties..., and knowledge about the requirements of the task."

Research by Baddeley (1972) and others indicates that stress associated with dangerous environments "affects performance through its influence on the subject's breadth of attention...but we still do not know what mechanisms mediate the effect of arousal" on attention span or even what is entailed in the adaptation to fear.

Evidence suggests that problem-solving abilities are affected by stress in much the way Janis indicates that decision-making is impacted. In particular, "if much of problem-solving involves the manipulation in consciousness of alternatives, choices, probable and possible outcomes and consequences, and alternative goals," then stress interferes with efficient problem-solving. Few alternatives are actually considered and the thought process is guided more by habituation and stereotyping than by the conscious weighing of alternative strategies. What is needed, he argues, is "fine-grained" analyses of these processes. "Preoccupation with the unstressed mind has restricted experimental work on these problems" (Mandler 1982:101). A related shortcoming is the failure to consider the social context of problem-solving behavior. The bulk of the research deals with individual tasks, not collective or highly interdependent tasks.

#### A Research Agenda: System-Level Responses to Stress

In the previous era when highly trained male pilots were selected as astronauts on the basis of physical stamina, high tolerance for stress,

psychological stability and technical competence for space missions involving relatively short-term exposure to multiple stressors in dangerous environments, less attention was paid to research on stress. In fact, Mandler (1967) noted in his early studies of highly trained astronauts a lack of anticipated stress responses; these men had been "trained to have available response sequences, plans and problem-solving strategies for all imaginable emergencies" thus emergencies were transformed into "routine situations" and therefore not experienced as stressful. At this stage in the space program endurance was the primary focus of both selection and training. Even space capsule design decisions were not frequently made in order to minimize environmentally induced stress or to increase "habitability" (Clearwater, 1985).

The future holds forth a different scenario. First, astronaut selection procedures have changed to include non-white males and scientific personnel as well as pilots. There is greater diversity among potential astronauts in occupational training, gender, age, ethnicity, and personality traits. Given this heterogeneity and the increased complexity and duration of space station missions, emphasis must now be placed (as Helmreich, 1983; Foushee, 1984; and other social scientists have argued) on the selection and training of highly compatible crews especially as group size increases to eight or more in relatively small modules. In addition, only recently has habitability become an integrated aspect of the space station design process. Alterations in selection processes to maximize crew compatibility and design decisions to improve habitability are essential ingredients. But as Danford et al. (1983) note in their chapter, "Humane Space Stations", social and organizational factors must

also be considered. Two specific factors have been isolated for consideration in this paper: (1) the social management of stress and development of interpersonal coping mechanisms, and (2) the socially efficient and productive management of interpersonal communications.

Development of a specific research proposal is beyond the scope of this chapter, however, research recommendations to NASA would include examination of existing data on crew interactions especially under stressful conditions to isolate effective interpersonal strategies for coping with stress and to identify particular interaction sequences which either exacerbated or mitigated stress responses. These data should be examined in relation to individual performance, group performance and interpersonal climate. Variation in interpersonal strategies by type and duration of stressors should also be investigated. In the early stages of the mission stressors may be predominantly physiological (e.g. resulting from space adaptation sickness or initial bodily responses to micro-gravity, etc.), however, as duration of the mission progresses psychological and social stressors may become more pronounced (i.e. intensification of the sense of isolation and confinement, monotony of the physical environment, and increased sensitivity to interpersonal incompatibilities, etc.). The most promising data sources for such analyses are likely to be tapes from the Skylab Missions given that they provide some insight into flights of analogous duration to planned space station missions.

Another useful focus of research would be investigation of group decision-making under stress. Existing data could be mined for insights

into the impact of stress on predicted cognitive and behavioral responses (e.g. the possible occurrence of hypervigilance), in decision-making situations of varying types. A separate research strategy would be to simulate group decision-making under stressful circumstances. One model for this type of research is the work by Foushee and his colleagues (e.g. Foushee and Helmreich, forthcoming) on crew performance under stress in aircraft flight simulations. Again, the aim would be to identify successful interpersonal strategies for coping with critical deficiencies resulting from stress. One potential byproduct of this research would be identification of the characteristics of computer decision-aides which would facilitate group functioning under conditions of high task interdependence and high stress. Information-seeking behavior, for example, could be isolated and analyzed for inefficiencies which could be meliorated by the proper use of expert systems or computerized search procedures. As Nickerson concludes in his chapter, "Stress is likely to be an important factor in the Space Station...Exactly how these factors, especially in combination, will affect performance and productivity is not known."

#### MEDIATED COMMUNICATION AND CREW PRODUCTIVITY

In a 1983 NASA-ASEE final report entitled "Autonomy and the Human Element," the authors state that the "general transmission and processing of information lies at the heart of almost every aspect of space station activity." Over the past decade information processing and communications have engaged more and more of the design capabilities of NASA both in terms of hardware and software development efforts. Rapid advances in

technology make this aspect of space station design especially volatile and vulnerable to obsolescence. While cost understandably plays a major role in design decisions, other factors affecting crew morale and productivity must be taken into account. Communication modality is also a critical factor in the coordination of activities aboard the space station. An intensive examination of the benefits and disadvantages of different modes of communication for within crew interactions, as well as for interactions between crew members and "ground" or mission control personnel, and for crew interactions with significant others is required. Morale, efficiency, productivity, the potential for conflict, the exercise of authority and control, and, ultimately, mission "success" are all affected by communication modality, access to information, and the structure of the communication channels.

#### Computer-Mediated Communication as Primary Modality

As Connors et al. (1985) put it "mediated communication systems must be developed to meet the needs of the crew throughout an extended mission." Such communication systems are not only vital to the ongoing mission of the space station, but may also be critical in maintaining social contact between station crew and ground personnel and thus contribute to the reduction in stress created by the sense of isolation and confinement. Maintenance of good communication links between the ground staff (e.g. "mission control" and other base operations) and the members of the space station crew are essential to the smooth functioning of the space station. Currently, one of the primary modalities for communication processes is computer-mediated interaction (Simes and

Sirsky, 1985). This section of the chapter includes a brief review of some of the relevant research on the impact of computer mediation on group interaction and decision-making. Other modalities for mediated communication are mentioned; however, cost factors necessitate heavy reliance upon computer-mediation.

#### Studies of the Effects of Computer-mediated Interaction

Siegel et al. (1986), in experimental studies contrasting the effects of face-to-face versus computer-mediated communication, find that with certain types of group problem-solving tasks there are marked differences between communication modes. Three types of communication modes were examined in the studies they report: face-to-face, simultaneous computer-mediated discussion and computer mail. While the results are not definitive, they suggest that communication mode affected the speed required to reach a group decision, the equality of participation rates of group members, communication rates, nature of the interpersonal communications, as well as the degree to which the group's decision deviated from individual's initial choices. The results indicate that there are certain advantages and disadvantages to computer-mediated communication systems which are relevant to plans for space station communications, although more systematic research is required.

Specific results of interest include the fact that computer-mediated simultaneous communication appeared to retard group decision-making when contrasted with face-to-face communication. In addition, this mode of communication fostered greater equality in participation rates among group

members, increased the number of inflammatory or "uninhibited" remarks and resulted in group decisions which deviated to a greater extent from initial individual choices than was the case when communication was face-to-face. (It should be noted that the subjects who participated in these groups had no prior association with one another.) Findings from the condition in which subjects communicated by computer mail were similar in most respects to the computer-mediated "conference" mode.

#### Implications for Space Station Communication Systems

The implications of the findings of Siegel et al. (1986) for decision-making and group problem solving aboard the space station are intriguing, though speculative. First, it would appear that complex problem-solving tasks, especially when time to solution is critical, are facilitated most by face-to-face communications even though this modality increases inequality in participation rates. The role of video connections in approximating face-to-face communication where physical copresence is not possible (as between crew members and family members or between crew members and mission control) has yet to be fully investigated. Limited research suggests that video contact (which is available to both parties) reduces perceived "social distance," but the role of perceived social distance in complex group problem-solving is not clear. Research varying both the complexity of the task and the degree to which face-to-face contact is mediated is needed.

Results concerning the effects of communication mode on participation rates also requires further investigation in relation to task complexity

and degree of task interdependence. The greater equality in participation rates fostered by computer-mediation may be functional for tasks requiring creative solutions (or during the "brainstorming" phase of group problem-solving) when maximization of input is essential.

Computer-mediation may also mitigate to some extent the effects of status differences on participation rates (a well-established finding in the small groups literature, see Bales work on the link between status and power and prestige orders and participation rates). Though the finding concerning the impact of computer-mediation on participation rates and its implications for the reduced effect of status differences is speculative, it certainly requires further investigation. Studies in which clear status differences exist among group members need to be conducted in computerized settings. Computer-mediation may facilitate the "upward flow" of negative information or information that challenges the positions of those in high status roles in the group. This effect is important since under time pressure or in stressful situations information is often critical to effective decision-making. Experimental research and simulation studies could be conducted on this topic. It appears that computer-mediation may mitigate the inhibiting effects of face-to-face communication when "subordinates" have access to critical information and may need to challenge authority or the group's dominant decision strategy (see Foushee, 1982, 1984, etc.). Connors (1985:174), for example, cites research indicating that "correctable pilot errors have gone uncorrected because of unquestioning attitudes, a lack of assertiveness, or deficient communication skills." Another intriguing result cited by Connors (1985:197) was obtained by Champness (1971) indicating that people are more likely to change their established positions on issues and reach a

compromise with other group members when communication is not mediated. This may have important implications for both the process and outcome of group decision-making aboard the space station.

Alterations in the norms surrounding communication content under varying communication modes also need further investigation. The normative restraints of face-to-face interaction on communication content are lessened in the more anonymous condition in which computers mediate interaction. As Siegel et al. (1986) note, computer-mediated communications included more inflammatory remarks. If this finding is observed in groups which have a history of interaction, then computer-mediation could foster interpersonal conflict and mechanisms to meliorate this possibility would have to be developed. A related concern is the protection of privacy in communications meant for family and friends, especially communications high in socio-emotional content. All forms of mediated communication raise issues of access as well as privacy which need careful examination in relation to individual morale, group cohesiveness and other dimensions related to the interpersonal environment within the space station. Connors (1985:197) cites studies indicating that mediated communication contains "reduced socio-emotional content," and thus is less effective for certain types of tasks such as negotiation or getting acquainted in contrast to tasks which require "the giving and receiving of information, asking questions, or exchanging opinions." Research on space station communications and the impact of computer-mediation on the performance of different types of tasks, as well as the nature of the interpersonal dynamics within the crew and between crew and ground is needed.

## Individual and Group Level Impacts of Computer-Mediated Communication Networks

Kerr and Hiltz (1982) discuss the potential impacts of computer-mediated communications on individuals and groups focusing on cognitive, affective and behavioral dimensions. They are concerned with broad effects at the organizational and societal levels, many of which go far beyond the scope and size of the space station. Some of the hypothesized effects have been verified in research discussed above by Kiesler and her colleagues (Siegel et al., 1986), but many of the topics raised by Kerr and Hiltz have not been subjected to systematic research. Furthermore, much of the evidence they cite is anecdotal, based on the experiences of those in positions to evaluate existing computer-mediated communication networks. Though computer-mediated communication networks of various sizes have existed for at least a decade, research examining the effects on specific variables related to group functioning and organizational effectiveness is fairly recent.

With respect to individual performance, Kerr and Hiltz (1982) discuss such issues as information overload, new skill requirements and improvements, expansion of learning opportunities, etc. as potential cognitive impacts of computer-mediated communication systems. Hypothesized affective impacts include: enhancement of the candor of opinions, potential "addiction" and heavy usage, increased network size and possible sources of social support (from kin, friends, and professionals), the ability to maintain friendships despite lack of

geographical proximity, etc. Negative potential consequences discussed include increased isolation from non-mediated communication relations, new sources of stress related to changes in existing patterns of work and communication as well as alterations in social networks, and the frustration created by the lack of immediate feedback, etc. Hiltz (1979), however, notes that in some cases, "The desire to have truly synchronous conferences seems to almost totally disappear as experience is gained on the system."

Of the individual-level behavioral impacts discussed, several are of primary interest. First, it is clear that computer-mediated networking increases connectedness among individuals thus expanding the scope and range of social relationships. According to Kerr and Hiltz (1982:114), computer-mediated communication systems lead to "increased collegial contacts, an increase in the number of contacts that can be maintained, and create the opportunity for regular connections with many people." Expansion of the actual or perceived social network through computer-mediated communication systems may help mitigate the sense of isolation experienced by space station inhabitants. Results indicate that a major strength of such systems is the ability to "keep in touch with others" (see Kerr and Hiltz, 1982:114, Vallee et al., 1978:111-115). In addition, such systems seem to alter the centrality of individuals by allowing those geographically (or for other reasons) on the periphery to regain a sense of centrality through increased communication contact.

Group-level impacts are especially relevant to space station design. Kiesler's work addresses some of the issues related to group

decision-making contrasting computer-mediated communication with face-to-face groups. However, Kerr and Hiltz (1982:121-122) identify a wide range of other group and organizational level impacts, some of which correspond to Kiesler's concerns. The group-level hypothesized cognitive impacts include: (1) the creation of "on-line" groups or "communities of interest", (2) improved group decisions, and (3) an increase in "knowledge-based authority," etc. With respect to group decisions, the findings cited are mixed. On the positive side results suggest that the capabilities of data base searches, increased access to information and access to decision-aides enhance group problem-solving and decision-making. As Turoff and Hiltz (1980:123) indicate "the computer can aid in gathering subjective estimates within a group" and facilitate the resolution of disagreements.

While Kerr and Hiltz (1982) indicate some empirical support for "at least the same quality of solution" when comparing computer-mediated to face-to-face groups (Turoff, 1980; Hiltz et al. 1981); Kiesler et al. (1984) and Siegel et al. (1986) report a decrement at least with respect to time to solution for the computer-mediated groups. Others, Kerr and Hiltz (1982) note, (see Johansen et al., 1979) argue that more conflict may result from the increased access to alternative views and that a "false sense of group consensus" may arise (Kerr and Hiltz, 1982:125).

On group problem-solving Kerr and Hiltz (1982:124) cite the work of Lipinski et al. (1980:158-159) which suggests that when considering, the "task-focused communications required by groups involved in joint problem solving, computer-based communication systems are appropriate in the

structuring, evaluating, and documenting phases of problem solving, since time delays are acceptable, written responses are appropriate, and face-to-face contact is not essential." However, they go on to state that the "implementing, searching, and conceptualizing stages of problem solving are less amenable to this technology." More research is needed concerning the phases of problem solving and the effects of computer mediation.

The following list includes some of the hypothesized behavioral impacts on groups identified by Kerr and Hiltz (1982:132-133). Many have not been sufficiently investigated to provide definitive evidence.

(Adapted from Kerr and Hiltz:)

1. Computerized communication increases cross-group communication.
2. It increases lateral network linkages among organizations.
3. It increases lateral network linkages within organizations.
4. Computerized communication may change social structures from pyramid or hierarchical to network-shaped.
5. It changes the centrality of members within groups.
6. It increases the possible span of control.
7. It can increase the effective limits on the size of working groups.
8. It increases the density of social networks, increasing connectedness.
9. It increases opportunities for decentralized communication.
10. Computerized communication may increase informal communications.
11. It changes who talks to whom.

12. Groups take longer to reach agreement and consensus is less likely.
13. Computerized communication sometimes makes it difficult to focus discussions.
14. Regularity of individual participation is sometimes difficult to enforce.
15. There is greater equality of participation than in conventional media.

#### Communication Network Structure, Centrality and Power

Prior research on communication networks in the social sciences provided evidence that the specific configuration or structure of the network affected the efficiency of problem solving groups. But more recent research tends to indicate that these results may not be valid for mediated communication systems. Subjects in various four-person network structures, given telephone contact capabilities, were able to come to consensus on group decision problems without much variation in degree of consensus or time to achieve consensus across structures (see Friedkin and Cook, 1987). Results from the computer-mediated version of this experiment are not yet complete.

Centrality has been linked to power in various studies of communication and in networks in which resources other than information are exchanged (see Freeman, 1979; Cook et al., 1983). In computer-mediated communication networks centrality is linked to access to information and control over the flow of information. To the extent that

computer-mediation alters these parameters decentralization of power may occur. Research is needed which examines the relationship between the structure of the communication network and control over information channels. Certainly as Kerr and Hiltz (1982:150) indicate "opportunities for decentralized communication are increased" in computer-mediated networks, "because it is easier to keep all those concerned with issues informed and up to date." Thus the efficient flow of information is enhanced. But efficient decision-making in groups in which communication is computer-mediated may require structured access to information rather than open access during the final stages of decision-making. Levels of access to information rather than the availability of communication channels becomes the critical determinant of positional centrality and thus power in this circumstance. Further research on these topics is needed.

#### Communication Networks, Authority and Control

Kerr and Hiltz (1982:125), among others, predict that computerized communication increases the "appreciation of knowledge-based rather than hierarchical authority." If this result is general, it will be important to study the conditions under which conflict can arise between knowledge-based and hierarchical authority structures. Efficient group functioning and problem solving is likely to be enhanced when there is minimal conflict between these sources of authority. Furthermore, hierarchical authority and command systems must be designed in such a way that information flow is not tightly hierarchically structured.

As noted above, in particular, in systems involving highly trained professionals the upward flow of critical information must not be circumvented by bureaucratic procedures or restricted communication channels. Maximization of group productivity and problem solving efficiency is likely to occur under conditions of open access to communication channels rather than strict hierarchical access under conditions of complex tasks, high uncertainty and a highly professionalized staff. Specific research on optimum alternative authority structures under varying communication network structures and task conditions is required.

With respect to authority and control in systems using computer-mediated communication networks, two additional impacts cited by Kerr and Hiltz (1982:150-151) are relevant. They argue (p. 150) that "greater delegation of authority is possible with the capacity for accountability and reviewing decisions in a timely and orderly manner." Second, they argue (p. 151) that it "increases the possible span of control" and "allows more centralized control over geographically dispersed units." Computerized decision-aides have the potential to alter both accountability and review procedures, but the specific extent and optimum role of these systems in human decision-making has yet to be determined.

Extension of the span of control and the degree of centralized control over units dispersed in space may become more important considerations during the post-IOC phase of the space station program. Some of these

issues as they relate to the potential for intergroup conflict have been addressed by Michener in his chapter in this volume.

#### The Impact of Computer-Mediated Interaction: Research Needs

Research on the impacts of computer-mediated interaction on individual and group-level functioning is relatively new. There are major limitations to existing knowledge in this area; results are more often based on anecdotal reports than systematic research or are derived from very limited observations over limited time spans in situations in which there is little control over the relevant variables. A major research program is required. Of particular importance in the design of space station configurations and communication systems is research on the links between information access channels and the exercise of authority and control. Various factors make the space station unique: the high degree of professionalization of the staff, the complexity of the tasks involved, the high degree of interdependence and uncertainty surrounding many of the tasks to be accomplished, the enormous information requirements, the difficulty and complexity of continual on-line monitoring, the spatial separation of the ground-based crew and command personnel from the space crew, and the potential existence of multiple authority structures.

Existing research is focused on earth based communication networks primarily among colleagues or remote members of interest groups where the exercise of authority is rarely an issue. Information exchange is frequently the primary or sole goal of the interaction. Thus extrapolation from the results of studies on these networks must be

treated as highly speculative. New research must be designed around the specific problems and parameters facing crews in space. Simulations could be designed which would mirror some of the most critical circumstances and used to evaluate alternative network structures, systems of controlled versus open access to information, given different types and levels of complex tasks. Problem solving efficiency and group productivity would be a primary focus of the research, although other issues such as increased social communication between crew members and ground personnel would also need to be addressed in terms of the impact on mission success, broadly defined. Priority should be placed on the development and evaluation of on-line data collection systems for post-IOC space station missions and other long-duration, "manned" missions concerning the multiple impacts of computer-mediated communication systems.

#### Summary Statement Concerning Research Needs

The 1986 Challenger disaster was as much a failure in organizational decision-making as a technical failure in the right rocket booster on the shuttle. This fact attests to the tendency in organizational contexts for scientists and managers to focus attention primarily on the technological aspects of systems rather than the social aspects of system design. Historically, in the social sciences, as well as the physical sciences, productivity has been viewed fundamentally as a problem of technical system or organizational design and innovation. Those who design and evaluate complex systems which require human participation, however, must eventually recognize the significant role of psychological and social factors in productivity. Human factors are now incorporated in NASA's

research program, but this is a recent and fairly small beginning given the time frame within which research commitments are necessarily made.

My recommendations assume that technical and social systems can not be designed in isolation of one another and that interdisciplinary research which crosses the invisible boundary between the physical and social sciences is required. Designing space stations which are maximally habitable and which optimize human comfort, satisfaction and productivity and minimize the sense of isolation and the stresses associated with risk and uncertainty, as well as the potential for intra-group and inter-group conflict is as critical a goal as the flawless design of structures which will provide the technical support for "life aloft".

Research on many critical aspects of social system design is simply not available. In part this is because the technologies under consideration are new (e.g. computer-mediated networks to facilitate interpersonal communication are relatively recent); but also in part, this state of the art is a function of national priorities and budgetary constraints. Hopefully, this situation will change. The quality of life in space in the twenty-first century will hinge upon decisions we make during this decade as to what research is necessary to maximize not only productivity, the bottom line for many, but also less tangible qualities such as habitability, sociability and liveability. The space station is, after all, a place to be inhabited, a mini-society which at some not too distant time in the future must begin to cope with not only the technological requirements of its environment, but also the psychological and social needs of its inhabitants and the social constraints and

requirements of an emerging society. Recruitment, selection, training, sustenance and replacement of persons will be as critical as the maintenance and replacement of parts.

The following is an abbreviated list of research needs (see Table 1) which I have suggested in the text of this report related to social factors involved in space station design during the post-IOC phase. The emphasis in this report has been placed on issues related to stress, its causes and consequences, and the impacts of computer-mediated communication systems (since that is currently the primary modality envisioned.) I have only scratched the surface.

In conclusion, it is important to note that as with many of the research programs of NASA and University-based scientists, the benefits to be derived from the proposed research extend far beyond the limited purposes of future space station missions. Improved methods for coping with multiple stressors in hostile environments and a better understanding of the social and psychological effects of computer-mediated communication systems have great potential applicability in a wide range of human social contexts. The payoffs for society as we know it on earth are potentially even greater than the payoffs for life as we envision it on space stations in the next century.

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TABLE 1 Selected Research Needs: Social Factors and Productivity on  
Long-Duration Space Station Missions

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Social Stress, Human Productivity and Group Functioning:

- (1) Develop more comprehensive and precise measures of stress levels for situations involving multiple stressors.
- (2) Research and develop stress monitoring systems, on-line data collection procedures, and more unobtrusive measures of stress.
- (3) Conduct research on personal characteristics (e.g. personality dimensions, gender, etc.) and specific responses to stress and adaptations to stress on long-duration space station missions.
- (4) Examine group composition factors which maximize efficient group functioning under multiple stressors.
- (5) Research the specific impacts over time of multiple stressors on individual and group decision-making processes. Assess the effectiveness of different coping strategies and decision aides under varying levels of stress and combinations of stressors.

- (6) Expand research on the causes of stress to include as well as psychological and physiological factors social factors such as group size, group composition, division of labor, workload, perceptions of equity in the assignments of tasks and responsibilities, styles of leadership, type and degree of contact with significant others, etc. on long-duration missions.
- (7) Begin to develop process models which relate stress to individual performance and group-level functioning and specify the conditions under which the impairment of individual performance seriously compromises group functioning.

Computer-Mediated Communication Systems, Human Productivity and Group Functioning:

- (1) Extend existing research on the social impacts of computer-mediated communication systems on individual decision-making and group problem solving.
- (2) Investigate the effects of computer-mediation in relation to the phases of group problem solving, complexity of the tasks and variations in the levels of environmental stress and uncertainty.

- (3) Conduct research on computer-mediated communication systems and the distribution of power and authority. Investigate in particular the potential for conflict between knowledge-based and hierarchical authority structures and the link between centrality and the exercise of power and influence.
- (4) Investigate the potential consequences of computer-mediated communication between crew members and significant others on earth attending to issues of privacy, social support and the effects on responses to isolation, confinement and other stressors on space station missions.
- (5) In the future, research the differential impacts on individual performance and group functioning of various types of mediated communication systems (including audio and video channels).
- (6) Examine factors related to communication modality and access to communication channels which inhibit the upward flow of critical information (especially negative information) and mechanisms which circumvent this problem.
- (7) Consider the effects of computer-mediated communication on the relations between crew members and ground personnel and between crews of different modules with respect to the potential for intergroup conflict and develop mechanisms to mitigate conflict.

NOTE: Other research recommendations are included in the text. This table includes a subset of the potential research topics relevant to long-duration missions.

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CONTROL, CONFLICT, AND CRISIS-MANAGEMENT  
IN THE SPACE STATION'S SOCIAL SYSTEM (YEAR 2000)

H. Andrew Michener

Department of Sociology  
University of Wisconsin  
Madison, Wisconsin

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[p.687 DOES NOT EXIST]

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#### REFERENCES

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THE SPACE STATION'S CREW AS A SOCIAL SYSTEM

This paper discusses the organization of the crew on board NASA's Space Station in the year 2000. In line with the work of Sells and Gunderson (1972), the perspective adopted here is that the crew of the Space Station is not just as a collection of people but a functioning social system. Crew members are viewed not just as individuals, but as interdependent parts in a larger structure.

Under current plans, the Space Station will evolve from its earliest form (called the Initial Operating Configuration, or IOC), which will exist approximately in year 1993, to a complex form (herein called the Second-Stage Operating Configuration, or SSOC) in year 2000. In the IOC (1993), the crew of the Space Station will be small (i.e., 6-8 persons). As the Space Station evolves over time, the crew will grow in size, and by SSOC (2000) it will have grown to 20-30 persons. It is possible, of course, to view the crew as a system even when there are only 6-8 people on board, as in IOC. However, it becomes increasingly useful to view human relations in system terms when there are more persons on board, as in SSOC.

NASA has traditionally placed great emphasis on careful selection and intensive training of its crews, and the outstanding performance of NASA crews aloft attests to the success of this approach. Selection and training will continue to play an important part in IOC and SSOC Space Station operations. Nevertheless, as the Space Station evolves from IOC to SSOC, NASA will find that it must rely less on selection and more on

intentional design of the on-board social system to achieve adequate performance by the crew. This will occur because the growth in size will render the crew increasingly less a collection of individuals and increasingly more a system with emergent properties.

During the evolution from IOC (1993) to SSOC (2000), important changes will occur in the social system on board. Not only will the system increase in size, but it will become differentiated into distinct subgroups and more complex in structure. These evolutionary changes will not only affect the Space Station's performance, but also determine the types of problems and failures that occur within the social system on board.

The main purpose of this paper is to assist NASA in developing a research agenda for the SSOC social system. It must be recognized, however, that neither the IOC nor the SSOC social systems exist today. This means that research is problematic, because there is no way that one can directly observe these systems or take measurements on them at this point in time. Since the IOC and SSOC social systems are yet to be developed, the essential question is not research, but planning and design--what shape and structure will these systems have and how will they function. Research becomes useful primarily as an adjunct to the design problem; that is, it becomes useful to the extent that it improves some social system designs or eliminates some candidate designs from further consideration.

To develop research ideas for SSOC, this paper first describes ways in which the SSOC social system will differ from the IOC social system. Next, it discusses three operating problems that may be more troublesome in SSOC than in IOC. These are (a) supervising and controlling the diversity of payload activities, (b) handling the relationship between differentiated subgroups of crew members, with its potential for intergroup conflict, and (c) responding to environmentally-induced crises. Finally, some avenues of research are suggested regarding these operating problems.

#### COMPARING THE IOC AND THE SSOC SOCIAL SYSTEMS

##### Social Systems in Space

Social systems in space operate under parameters different from social systems on Earth. These parameters, which apply to both the IOC and SSOC social systems, include:

(a) Perilous Environment. In contrast to most Earth-based social systems, the crew on board the Space Station (and on any space vehicle) will face a perilous environment (microgravity, no oxygen) and require complex life-support. Crew members will face significant hazards and risks to life.

(b) Relative Isolation. The social system on the Space Station will be isolated from other social systems and (in many respects) self contained. It will be in contact with Earth only via telecommunications,

and hence it potentially has some degree of independence from Mission Control on Earth.

(c) Long Duration. The social systems on board the Space Station, while transitory compared with those on Earth, will remain in space for increasingly long durations. Space Station crew members will fly missions that endure 90 days. (The Space Station itself may continue usefully in orbit for 20-30 years.) From the standpoint of individual crew members, long-duration missions may entail stress, psychological depression, and diminished performance (Bluth, 1980, 1981; Cunningham, 1977; Oberg, 1981).

#### Exogenously Mandated Changes in SSOC

The environment faced by the Space Station's crew in SSOC will be just as perilous as that in IOC. However, the Space Station's social system will not remain constant. NASA has already mandated certain changes in the social system that are to occur between IOC (1993) and SSOC (2000). These changes include:

##### Change in Crew Size

One difference between IOC and SSOC is the size of the crew on board the Space Station. In IOC, the crew will be small (6-8 persons). In SSOC, the crew size will be larger, perhaps 20-30 or even more. This increase in size will be made possible by the physical expansion of the Station. Most of the added crew members in SSOC will be Payload Specialists, not Astronaut Pilots.

## Change in Crew Composition

Several important changes in the composition of the crew will occur between IOC and SSOC. First, the Japanese and European Space Agencies will attach modules to the Space Station in SSOC and place their own Astronauts aboard. Whereas the IOC crew will consist of USA-NASA personnel, the SSOC crew will include substantial numbers of several distinct nationality subgroups: USA, Japan, Europe.

A second change to occur concerns the skill mix of the crew. In IOC, most crew members will be Astronaut Pilots. In SSOC, there will obviously still be some Astronaut Pilots on board, but the crew will include many more Payload Specialists than in IOC. Some calculations illustrate this point. If it takes two Astronaut Pilots to fly the Space Station at one time, then a total of four persons will be needed to fly the Space Station around the clock (assuming that flight operations are never left unattended and that Astronauts work 12 hours at a stretch.) The implication is that, in IOC, at least half the crew members will spend their time flying the Space Station, not conducting payload operations. The situation in SSOC will be more favorable, because the number of persons needed to fly the Space Station will presumably remain about the same (despite the larger physical size of the Station); most of the additional persons on board in SSOC will be Payload Specialists, who can devote their time to scientific or manufacturing productivity.

A third change, less well defined at this point, concerns the gender mix of the crew in SSOC. NASA has shown that it intends to put women in space, although missions to date have been male dominated. Presumably the crew of the Space Station will include some women. With the move from IOC to SSOC, and the accompanying increase in crew size, there may be opportunity to move the ratio of females/males on board closer to 1.00, should NASA opt to do this.

#### Change in Mission Statement and Goals

In IOC, the primary mission goals will be, first, to fly the Space Station and, second, to construct large space structures, i.e., expand the physical structure of the Space Station using components flown up via the Shuttle (Danford et al., 1983). These goals will doubtless apply to SSOC as well.

In SSOC, however, the increased number of Payload Specialists on board will permit other goals to be pursued. These goals may include manufacturing and materials processing under conditions of micro-gravity, and tending and repairing communications satellites. Other objectives may include conducting scientific experiments, carrying out remote sensing and meteorological monitoring, and engaging in flight support (assembly, maintenance, checkout, launch, recovery) for manned or unmanned LEO transfer missions (Danford et al., 1983). Overall, the goals pursued by the crew members in SSOC will be more complex and diverse than those in IOC. Expressed more formally, the SSOC social system will be attempting

to optimize what may be construed as a highly complex multi-objective function (Keeney and Raiffa, 1976).

#### Change in Onboard AI and Computerization

Current plans for the Space Station call for an increasing use of artificial intelligence (AI) and expert systems over time. The extent to which AI can be used in IOC and SSOC depends both on the capabilities of the Space Station's computers and on the software itself.

In past missions, the computers on board NASA's space vehicles have not been powerful, due in part to limitations imposed by physical size and weight. The situation will be somewhat better in IOC. Plans indicate that IOC will include some AI systems, although these will be small-to-moderate in size. NASA will, of course, use mainframe computers on Earth, and these may supplement the AI routines of the Space Station's smaller onboard computers. Some AI systems on board will probably serve as consulting devices for the diagnosis of hardware failures. Other onboard computerization may involve scheduling of crew activities and maintenance of databases (e.g., materials inventory).

By SSOC, the computers on board the Space Station will be faster and capable of running large AI programs. Moreover, the software will have evolved with experience on board the Space Station, and will become more wide-ranging in its capacities. Thus, AI and expert systems will be more prominent in SSOC than in IOC, and SSOC will be more automated.

From the standpoint of the social system, the evolution of computerization is relevant because AI will become integral to onboard decision-making. By SSOC, the AI software will be able not only to diagnose hardware failures, but also to schedule human activities and perhaps even to resolve conflicts among humans regarding priority of objectives.

### Induced Structural Changes in SSOC

The exogenous changes mandated by NASA for SSOC, as listed above, will bring about many changes in the internal organization of the SSOC social system. Of course, because neither the IOC nor the SSOC social systems exist today, one cannot draw firm conclusions about their structural properties or performance under specified conditions. Nevertheless, by considering the proposed systems in light of research findings on Earth-based social systems and earlier space-flight social systems, some plausible conjectures can be made regarding their structure and performance. It seems fairly clear that the SSOC social system, as contrasted with the IOC system, will be more complex, more differentiated into subgroups, and more decentralized with respect to decision-making.

### Complexity

The SSOC social system will be far more complex than that in IOC. The SSOC social system will include more members (20-30, rather than 6-8), and the complexity of the system will increase nonlinearly with crew size. The primary source of this increased complexity is not just larger crew

size per se, but rather the fact that the system's growth will occur via differentiation (elaborated subgoals and subgroups) and not via segmentation (Sutherland, 1975; Casti, 1979).

This increase in complexity is reflected, for instance, in the number of communication channels in IOC as contrasted with that in SSOC. With 8 crew members in IOC, there are 28 channels (assuming that each channel is 2-way and that a crew member does not require a channel to communicate with himself); with 30 crew members in SSOC, there are 435 channels. Thus, a 4-fold increase in crew size produces a 16-fold increase in channels. Of course, it may be the case in SSOC that every crew member will not have a need to communicate with all others, but the increase in structural complexity is nevertheless clear.

Increased complexity will show up not merely in structural measures but also in functional ones. For instance, complexity might become apparent in slower response to emergencies or crises. Today there is no way to measure the response-time performance of the SSOC social system. Could one do this, however, the SSOC social system might emerge as slower (and less predictable) than the IOC system when responding to such emergencies as fire on board or a collision with space debris. To mobilize 20-30 persons scattered in several modules (in SSOC) will probably take more time than to mobilize 6-8 in one module (in IOC).

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## Differentiation

The social system in SSOC will be far more differentiated -- that is, composed of subgroups with distinct identities -- than the social system in IOC. The bases for this differentiation will be national origin and task specialization; there may also be some subgroup differentiation based on gender.

Under current plans, NASA will add physical modules to the Space Station between IOC and SSOC, causing an evolutionary expansion in size. NASA itself will supply some modules, but others will come from foreign space agencies (Japan, Europe). Hence, the crew on board the SSOC Space Station will consist of persons from all three space agencies (USA, Japan, Europe), possibly in proportion to the financial contribution by various participating nations. This means the SSOC crew will consist of subgroups that (a) have different national origin (US, Japan, Europe -- Britain, France, Germany, Italy), (b) have different native languages, (c) have different skin color and racial characteristics, making group membership readily visible, (d) have different moral and religious belief systems, and (e) perhaps have different goals and long-term agendas. This SSOC crew profile differs sharply from the far more homogeneous IOC crew profile; in IOC the crew will be single nationality (primarily or entirely USA), single language, consonant beliefs, unitary goals, single command structure on the ground (NASA), etc.

Crew members from the three space agencies will, at least to some degree, constitute distinct subgroups on board the SSOC Space Station. Of

course, the use of a single language (English) on board will help to lessen subgroup differentiation. Nevertheless, an extrapolation from research on Earth-based social systems suggests that differences in the factors noted above (nationality, skin color, native language, belief systems), reinforced by NASA's plan to house together persons from a given country in their own module, will cause the subgroups to have at least a moderate degree of in-group identification and well-defined boundaries (Tajfel and Turner, 1986; Wilder, 1986; Brewer and Campbell, 1976).

Another basis for subgroup differentiation present in SSOC (but not in IOC) is task specialization. As noted above, both IOC and SSOC will have Astronaut Pilots, but SSOC will have many additional Payload Specialists. The SSOC crew, for instance, may include such diverse specialists as a university astrophysicist, a commercial materials engineer, and a national security intelligence analyst.

The Astronaut Pilots in SSOC may view themselves as a distinct subgroup within the larger social system. They will have similar backgrounds, perform similar activities, and work for the same employer on the ground (NASA). Whether the Payload Specialists in SSOC will view themselves as a second distinct subgroup is less clear, because they may differ significantly among themselves. That is, the Specialists will come from a range of educational backgrounds, work for different employers on Earth, pursue a diversity of objectives while on board the Space Station, and perhaps even operate under orders to keep their activities secret from others on board. If some Payload Specialists work interdependently on tasks or report to similar commands on Earth, there is the possibility

that they will form identifiably distinct, functioning subgroups on the SSOC Space Station.

#### Decentralization

The social system in SSOC will be more decentralized than that in IOC. In other words, decision-making will be distributed more widely across persons in SSOC than in IOC. Supervisory control over various functions will shift away from a central command and reside instead with a diversity of specialists.

Pressures toward decentralization of decision-making and control in SSOC will come from several sources. First, as the Space Station evolves from IOC to SSOC, there will be a change in the Station's mission. Payload operations will become more prevalent and important. As a result, the activities on board will become more differentiated and specialized (e.g., materials processing under microgravity, satellite servicing, and conduct of experiments). Most of these new activities will be expertise-based, and they will be controlled by the only persons on board who know how to do them (i.e., Payload Specialists, not Astronaut Pilots). The expansion of expertise on board in SSOC will coincide with decentralization of decision-making.

Many Payload Specialists in SSOC will be employees not of NASA, but of other organizations on Earth. One implication is that the Payload Specialists presumably will report to different supervisors on the

ground. This fact will conduce toward more decentralization of decision-making on board the Space Station.

#### OPERATING PROBLEMS FACING THE SSOC SOCIAL SYSTEM

As detailed above, the social system on board the Space Station will undergo significant structural changes from IOC to SSOC. The system will experience a change in mission statement, grow in complexity, differentiate into subgroups, and decentralize in decision-making. These shifts will produce operating problems for the SSOC social system that were not present in IOC. Although one can doubtless identify many such problems, three are of special interest here. These are singled out not only because they pose special threats to overall mission performance, but also because they potentially can be mitigated (if not eliminated) through design and research efforts. The three are:

(a) The SSOC system will face problems with supervisory-control functions that were not present in IOC. The burden of coordination will be greater, because the SSOC system will include distinct national subgroups as well as more task-specialization subgroups than IOC. Coordination of activities will be more problematic in SSOC, in part because decision-making will be more decentralized.

To some degree, the problems with supervisory-control functions can be addressed through design efforts prior to SSOC. The broad research/design issue for NASA is what type of supervisory-control structure will best

serve the SSOC system, in the sense of providing greatest efficiency and highest probability of mission success.

(b) The SSOC system will pose risks of intergroup conflict that were not present in IOC. The presence on board of several distinct subgroups, with potentially opposing interests and objectives, increases the prospect of conflict.

The broad research/design question for NASA is what safeguards to build into the system to reduce the probability of overt conflict occurring. A related question is what can be done to assure that any conflicts that do arise are resolved constructively.

(c) The SSOC system may have more difficulty than the IOC system in coping with crises (e.g., fire on board, collision with space debris, etc.). The SSOC social system will probably have more resources than the IOC system for coping with many crises. At the same time, the SSOC system -- with its greater degree of differentiation and decentralization -- may be worse-off organizationally than IOC and have more difficulty mobilizing to deal with crises.

The broad research/design question for NASA is how best to structure the SSOC social system so that it can mobilize adequately to deal with various crises.

The following sections discuss each of these problems in turn. Primary focus is on the nature and genesis of the problems. Attention is also

given to design issues -- that is, to what research might be done by NASA prior to SSOC to mitigate these problems.

#### SUPERVISORY-CONTROL AND OPTIMAL PERFORMANCE

The topic of supervisory control by humans on board the Space Station has several dimensions. First, there is the matter of humans' reliance on and control over machines. Under current plans, the Space Station's physical subsystems will include many sensors and control devices to monitor and regulate automatically a variety of outcomes, including life-support, power sources and management, flight control, thermal control, and traffic control. Thus, when interfacing with machines, the crew members on board will enter the Space Station's control process only in a high-level monitoring, troubleshooting, and decision-making capacity (Kurtzman et al., 1983; Von Tiesenhausen, 1982).

A second aspect of supervisory control on the Space Station is the regulation of crew members' activities by other crew members. This topic is of interest here because there will be a shift in the Space Station's onboard supervisory-control structure during the evolution from IOC to SSOC. The following discusses some aspects of this change.

#### The Supervisory-Control Structure

As used here, the term supervisory-control structure refers to that functional subsystem on board the Space Station which (a) regulates crew activity in the interest of attaining system goals, (b) makes choices

among collective behavioral alternatives, and (c) handles dissent, including the treatment of noncompliance by crew members.

In social systems on Earth, supervisory-control structures (often called "authority" systems) typically specify who makes what decisions, who evaluates whose performance, and who influences (gives orders to) whom. No doubt the supervisory-control structure on the Space Station will entail such specifications, with the added characteristic that some prerogatives will reside with crew members on the Space Station while others will inure with NASA personnel on the ground.

Supervisory-control structures can assume a wide variety of forms. For instance, at one extreme there is the archetypical military command model with hierarchical lines of authority and command. In pyramidal structures of this type, control flows from the top down, while information flows up (Mesarovic et al., 1970). At another extreme there is the equalitarian model with a flat authority structure. In the Space Station context, such a model might consist of equally-ranked Astronauts aloft, not taking orders from a crew member on board, but each reporting to someone on Earth. A third supervisory-control structure -- falling between the extremes of hierarchy and equality -- is the heterarchy. A heterarchical structure is one that resembles a network, the nodes of which are relatively independent control systems and the arcs of which are the lines of communication passing between the nodes (Sutherland, 1975). On the Space Station, the nodes in such a structure might be individual Task Specialists, or possibly teams of Specialists.

It follows that one important research/design issue is exactly which supervisory-control structure should be deployed on board the Space Station. Since this issue is important both in IOC and in SSOC, it is useful first to look briefly at the IOC situation.

#### Supervisory-Control Structure in IOC

The main objectives of the Space Station crew during IOC will be to fly the Station and to expand its physical structure (add new habitation modules and platforms). Any of several alternative supervisory-control structures might suffice in IOC to accomplish these objectives, although some structures are probably better than others. The question, then, is which to deploy. NASA might base its choice on such procedures as trial-and-error or extrapolation from previous experience with space flight supervision. Alternatively, systematic research could be used to narrow the choice by eliminating some candidate structures.

More specifically, NASA might conduct simulations on the ground to test various outcomes from different supervisory-control structures. Simulations might be done under conditions that closely replicate those found in space -- e.g., high stress, high noise, restricted communication, 90-day duration, tasks similar to those done in space, and so on. Important outcome measures include productivity levels, crew satisfaction, lack of conflict, adequacy of response to emergencies, etc. Multiple replications could be run on each of several alternative supervisory-control structures using standard experimental designs. The

results should provide a fair idea of how the alternative supervisory-control structures will perform.

Without the results of such research, it is hard to know what type of structure will eventually be deployed. A plausible conjecture, however, is that the Space Station's IOC supervisory-control structure will, at least to some degree, resemble a standard "military command model" with hierarchical lines of authority and command. There is a general tendency for groups facing perilous environments to organize themselves hierarchically, primarily because it strengthens their capacity to respond to emergencies and crises (Helmreich, 1983; Harrison and Connors, 1984). This pattern occurs not only in space missions, but in submarines, underseas research vessels, North Sea oil rigs, and polar expeditions. Most likely, the IOC system will be no exception.

Thus, the supervisory-control structure on board during IOC will presumably involve a designated "Mission Commander" (or some such title) with authority to issue orders to subordinates. Of course, the 6 or 8 Astronauts on board during IOC are going to be competent, skilled, and resourceful persons. They will have been selected via a rigorous screening process, and there will be little reason to doubt their capacity for decisive action. Nevertheless, their roles will be fairly restrictive and afford little independence, and they will essentially be taking orders from Mission Control on Earth and from their Mission Commander on board the Space Station.

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Relations Between the Crew and Mission Control

Both in IOC and in SSOC, one research/design issue deserving consideration by NASA is the exact allocation of control between Mission Control on Earth and the crew on the Space Station. The viewpoint taken here is that the Space Station will not be "autonomous" or independent of Mission Control. Because many monitoring and control functions are better performed on the ground than in space, Mission Control will exert considerable influence over a wide range of crew members' activities and decisions throughout IOC. Crew members, however, will probably retain control over such things as the inventory of items on board the Space Station and the flow of traffic in and around the Space Station.

More problematic is whether crew members will have control over the scheduling of their own day-to-day activities. On one hand, Mission Control needs assurance that crew members are performing adequately and thus may wish to exercise strong supervision over schedules. On the other hand, tasks which are easy to perform on Earth may consume great time and energy under microgravity in space (Sloan, 1979). This may cause Mission Control to expect too much and could lead to overscheduling of daily activities by personnel on the ground.

Excessive regulation of crew schedules by Mission Control can produce role overload on space missions (Helmreich et al., 1979). Even worse, lock-step regulation of the crew's schedule by Mission Control might result in such labor problems as the well-publicized one-day "strike in space" that occurred during the 1973 Skylab mission (Balbaky, 1980;

Cooper, 1976). To achieve a workable balance, what the Space Station needs is an arrangement whereby Mission Control can specify (longer-range) goals to be achieved, while crew members can express and to some degree enforce their preferences regarding local work flow and task-allocation.

One approach to such an arrangement is based on experience in earlier space missions. Both the Russians and Americans have reported some success with task-assignment procedures whereby decisions regarding mission and related tasks are made under the hierarchical model, and decisions regarding off-duty activities and living arrangements are made democratically (Leonov and Lebedev, 1975; Nelson, 1973). Although promising, these results pertain primarily to short-duration missions, and their applicability to longer-duration missions is still an open question subject to further research.

Another approach to the issue of day-to-day task scheduling is to rely heavily on computer software. This approach will be relevant in SSOC, and may also be applicable in IOC. Many large projects of various types are managed on Earth today via project planning software. Task scheduling on the IOC Space Station will probably not be so complex as to require software more elaborate than that available today. In fact, computer software for project management on the Space Station will not only be useful in achieving optimal allocation of tasks to crew members, but may even emerge as a tool for conflict resolution between the Space Station crew and Mission Control.

## Supervisory-Control Structure in SSOC

As noted above, the social system in SSOC will be larger, more complex, more differentiated, and more decentralized than that in IOC. In consequence, the supervisory-control structure in SSOC will be more elaborate than that in IOC and probably will assume a fundamentally different form.

### Functions of Supervisory-Control in SSOC

The SSOC supervisory-control structure must be geared to handle many of the same functions as the IOC system. These include flying the Space Station, coordinating with Mission Control on Earth, and building (expanding) the Space Station. In addition, it will have to handle other functions, such as processing materials and servicing satellites, as well as serving as a node in a larger communication and transportation network in space.

The SSOC social system will include not only Astronaut Pilots, but also a large number of Payload Specialists (perhaps as many as 20 of them). Regulation of these Specialists may prove a complicated task. Most Payload Specialists will be highly educated professionals knowledgeable in their respective specialties. Many will be accustomed by prior employment to working under supervisory-control structures permitting a high degree of independence and autonomy. On the Space Station, they may be performing activities (such as research) that are best accomplished under decentralized decision-making, and they will

probably be working for someone other than NASA (reporting to non-NASA authority on Earth). One implication of these facts is that a straightforward extrapolation of the hierarchical IOC military command model to SSOC will not suffice.

#### Morphology of Supervisory-Control in SSOC

It was suggested above that NASA might use experimental research (simulations) to design the initial IOC supervisory-control structure. A similar approach would be applicable to the design of the SSOC control structure. In the absence of such research, however, it is a plausible conjecture that the supervisory-control structure in SSOC not resemble a military hierarchy to the same extent that the IOC structure did (Helmreich, 1983; Danford et al., 1983; Schoonhoven, 1986). Instead, it may more nearly resemble an industrial heterarchy. This is a structure in the form of a network, the nodes of which are relatively independent control systems.

Due to task specialization, decision-making within SSOC will be more decentralized than in IOC. Interaction will be more collaborative, collegial, and advisory. To a significant degree, influence will flow in many directions (not just top-down) and will be based on expertise and control of information as well as on organizational status. Despite all this, however, Payload Specialists in SSOC will not be truly autonomous or independent. They may have more decision-making prerogatives than Specialists in IOC, but their discretion will nevertheless be circumscribed and their performance will doubtless be subject to

administrative regulation and review. Much of this administration will originate from (non-NASA) personnel on the Earth, not from other persons on board the Space Station.

On the Space Station itself, many Payload Specialists in SSOC may be organized into small teams (2-, 3-, 4-persons, etc.) working on specific tasks. This team structure will capitalize on the added productivity that results from such processes as social facilitation (Zajonc, 1965; Henschy and Glass, 1968; Marcus, 1978); at the same time, it will permit the Space Station's crew to tackle a diversity of unrelated tasks requiring different competencies (research, materials processing, satellite servicing, construction, etc.) The teams constituting the nodes of the heterarchy will each have decision-making authority regarding work-flow on their own task (doubtless with the consent of supervisors on Earth).

In addition to this structure, the SSOC system will likely include a small administrative staff -- e.g., a Mission Commander and several lieutenants who will be responsible for coordinating relations among the diverse projects on board the Space Station. These administrators will have the power to halt or reschedule activities on one project in order to facilitate another. (Again, coordination of this type will require the concurrence of Mission Control on Earth.) Moreover, these administrators will also have the capacity, if an emergency or crisis arises on board, to halt all task activities and to mobilize the entire crew to cope with the emergency.

In sum, it is suggested that the supervisory-control structure in SSOC will probably differ from that in IOC, and may assume the form of a heterarchy or quasi-heterarchy. This statement, however, can be no more than a conjecture. It has been proposed that NASA might use simulation research on alternative supervisory-control structures as a basis for developing the design of the SSOC system.

#### Leadership Roles in SSOC

The model of the supervisory-control structure sketched here assumes that, in SSOC as in IOC, there will be an overall Mission Commander on board the Space Station. The exact nature of the Mission Commander's role is an open research/design issue. It seems clear, however, that his role during SSOC will be different from that during IOC, for he will coordinate and oversee rather than give directives, military-style. Although he will have the skills to fly the Space Station, he will not handle the minute-to-minute task of piloting the Station. Nor will he carry out many payload operations per se. Instead, his major role will be to coordinate flight operations and payload operations, as well as coordinate relations among nationality subgroups on board and with Mission Control on Earth.

Beyond the nature of the Mission Commander's role, there is the question of what persons might be candidates for that role. Whether the position of Mission Commander in SSOC will be restricted to NASA Astronauts or open to crew members from Japan and Europe is yet another research/design issue for NASA to address. A similar issue, too, arises

with respect to the lieutenants and other officers on board the Space Station.

## THE POTENTIAL FOR CONFLICT IN SSOC

### Risks of Conflict in SSOC

Conflict in social systems can manifest itself in diverse forms. Typical forms include argumentation, social "friction," interpersonal disliking, attitudes of distrust, passive refusal to cooperate, and so on. Of course, when conflict becomes severe it will emerge in still other forms such as physical violence.

Although the evidence on this point is largely anecdotal, relations among crew members in earlier NASA space flights have been harmonious. There is little evidence of serious conflict or disagreements among crew members themselves. There is, however, some evidence that disagreements have occurred between space crews on one hand and Mission Control on the other (Pogue, 1985; Balbaky, 1980; Cooper, 1976). The source of these conflicts appears to have been task overload or lock-step regulation of crew activities imposed by Mission Control.

Except for the longer flight duration, there is no reason that conflict in the IOC social system will be greater than that during previous NASA space flights. There may again be some disagreements

between the crew and Mission control, but probably not much conflict among crew members themselves.

In SSOC, however, the situation is different. There is more potential for interpersonal and intergroup conflict in SSOC than in IOC.

#### Sources of Conflict in SSOC

The risks of conflict are higher in SSOC than in IOC because the crew will be differentiated into subgroups and decentralized with respect to decision-making. First, SSOC will include many more Payload Specialists than IOC. Each such person will have his or her special goals, which means that the SSOC Space Station will be pursuing more complex (multi-objective) goals and that decision-making will be more decentralized than in IOC. These diverse goals may be (somewhat) incompatible, and coordination will be more problematic.

Just as significantly, the inclusion in SSOC of several nationality groups with distinct identities (USA, Japan, Europe) creates the potential for intergroup conflict. Whether conflict actually erupts among members of different subgroups depends on incompatibilities among the different roles, values, and goals of these persons. The fact that these subgroups will be housed in distinct physical modules will probably heighten cohesiveness within the subgroups and thereby increase the likelihood of friction between subgroups. The added fact that Americans may be in the minority (or, at least, not in the majority) on board the Space Station in SSOC could make the situation even more volatile.

Although it may be only partially relevant to SSOC, research on Earth-based systems shows that integration is problematic in social systems having many subgroups. Systems of this type are more vulnerable to higher levels of conflict, mis-coordination, lack of cooperation, and mistrust than are systems having no subgroups. Not surprisingly, conflict between subgroups is especially likely to occur when they have divergent objectives or interests (Campbell, 1965; Sherif et al., 1961; Diab, 1970). Moreover, when conflict does occur in social systems of this type, it often is more severe (i.e., more rancorous, more divisive, more difficult to resolve) than that occurring in systems having no distinct subgroups. This happens because, in systems with distinct subgroups, conflict is not just disagreement among persons as individuals, but among persons as agents of subgroups.

In sum, NASA has chosen to deploy a heterogeneous, differentiated SSOC social system in which the risks of conflict are higher than would be the case in certain other types of social systems. The risks would be less severe, for instance, had NASA chosen to deploy an SSOC system more like that in IOC -- i.e., a system where crew members have a uniform nationality (USA), single native language, unitary goals, centralized command structure on the ground (NASA), single living module, and so on.

#### The Importance of Avoiding Conflict

No assertion is made here that conflict, mistrust, and lack of coordination are inevitable in the SSOC social system. It is merely being

suggested that conflict is more likely in SSOC than in IOC. Conflict occurring in SSOC will probably be of low-to-moderate intensity (not severe intensity), and will probably appear in such forms as argumentation, friction, and distrust (not physical violence). There will be no need to install a jail on the SSOC Space Station.

It is assumed here that NASA will wish to avoid conflict in SSOC. The primary reason for this is cost. The dollar expense per crew man-hour aloft is very high (est. \$40,000 per man-hour), and it is obviously undesirable to waste time through lack of coordination or, worse, through the need to resolve open conflict.

A second reason for avoiding conflict in SSOC is that conflict in social systems often feeds on itself. That is, an initial conflicted encounter may lead to hard feelings, disliking, and attitudes of distrust toward out-group members, as well as the development of cognitive biases and stereotypes (Wilder, 1981; Brewer, 1986; Wilder and Cooper, 1981). This makes subsequent cooperation harder to achieve, and may even intensify the problem (i.e., "escalation of conflict"). Interpersonal conflict changes the attitudes and beliefs of people involved, and this change is often for the worse when viewed from the standpoint of system performance (Cooper and Fazio, 1986; Michener et al., 1986; Pruitt and Rubin, 1986).

In the following sections, then, consideration is given to various means by which NASA, through its design efforts, can reduce the risk of conflict among the crew in SSOC. These means include the alignment of

goal structures, patterning of social interaction, and selection and training of crew members. The fundamental research/design issue underlying this discussion is how to design the SSOC social system to avoid or minimize interpersonal conflict; a related issue is how to equip the crew with techniques to resolve conflict (if it occurs) in a manner that is constructive from the standpoint of the larger system.

#### Conflict Avoidance via Goal Structure

Various approaches are available to NASA for avoiding and/or reducing conflict in the SSOC social system. One of the more effective is to give close attention to the design of, and alignment among, subgroup goals.

#### The Importance of Goal Alignment

As noted above, opposition of interests among subgroups in differentiated social systems is an important factor producing conflict. With opposition of interests, overt conflict frequently occurs; without it, there is no reason for conflict to occur (Campbell, 1965; Sherif et al., 1961)

In IOC, there will not be much opposition of interests among crew members. The Space Station will have a single coherent goal (i.e., an objective function that specifies what should be maximized by system performance). The main mission will be to fly the Space Station and to carry out evolutionary expansion of the Station via construction. Crew members will not be working at cross-purposes. In contrast, during SSOC

the Space Station will have a more complex objective function. It may even have more than one objective function because, in addition to the function for the entire system, there may exist separate sub-functions for each of the subgroups on board. Conflict might arise, for instance, over manpower scheduling or over allocation of scarce resources such as electrical power. In SSOC there will be at least some risk that one or several subgroups on board may have (or develop) goals that do not mesh smoothly with those of other subgroups.

An important research/design issue for NASA is to specify objective function(s) for the SSOC crew such that the attainment of goals by one subgroup does not prevent the attainment of goals by some other subgroup(s). Well-conceived objective functions will promote harmony and productivity; conversely, ill-conceived or misaligned goals will doubtless generate interpersonal and intergroup conflict.

#### The Superordinate Goals Approach

One approach to aligning goals among SSOC subgroups is to establish objective functions that embody what are called "superordinate goals" (Sherif et al., 1961; Blake and Mouton, 1968, 1976, 1984). A superordinate goal is one that (a) is held to be important by each of the subgroups comprising the larger social system and (b) can be attained only through cooperative interaction among subgroups (i.e., cannot be attained by a single subgroup acting alone). Superordinate goals induce a high coincidence of interest among diverse subgroups.

Research on Earth-based social systems has shown repeatedly that superordinate goals inhibit conflict among subgroups. Moreover, in social systems where the subgroups are already engaging in open conflict, the introduction of new superordinate goals can mitigate or resolve conflict (Sherif et al., 1961). Superordinate goals reliably improve cooperation and reduce conflict among subgroups in a larger system.

There may be several ways to incorporate superordinate goals in the design of the SSOC social system. One particularly interesting possibility is to include such goals in the computer software used on board the Space Station. This becomes especially viable if NASA uses some kind of "project scheduler" software to assign tasks to crew members. Software of this type entails optimization in some form or another; when designing this software, NASA will have to decide exactly what is to be optimized. It is suggested here that what should be optimized in SSOC is not merely "productivity," but also system integration. Both concerns are important. The design and use of project scheduler software provides an opportunity to expressly incorporate goals that bind the subgroups together.

#### The Game-Theoretic Approach

An alternative approach to goal design is to treat the relations among subgroups in SSOC as a set of n-person games (Shubik, 1982, Owen, 1982, Vorob'ev, 1977; Leitman, 1976). That is, the subgroups in SSOC might be viewed as players having (somewhat) opposing interests in n-person non-constant-sum games. These games could be analyzed to identify points

of contention between subgroups and likely outcomes of conflict.

Specifically, one might first identify a set of scenarios (situations) that could arise on board the Space Station, and then treat each of these as a distinct n-person game. These scenarios might include such events as EVAs, health emergencies, payload experimentation, space debris emergencies, etc. Each could be analyzed in terms of the likely equilibrium outcome under some solution concept (e.g., the Nash non-cooperative equilibrium). Results of such an analysis would show the extent to which the subgroups have opposing interests and indicate whether they would play a strategy leading to an outcome that is not desirable collectively (i.e., not Pareto optimal).

The point of conducting such an analysis is not only to anticipate issues over which conflict might erupt, but eventually to design the subgroups' objective functions to assure that the payoff matrices for most n-person games played on board lead to a benign equilibrium.

Persons within NASA are familiar with the game theoretic approach; NASA used game theory to resolve conflict among groups of engineers with competing demands regarding equipment to be placed on the Mariner spacecraft. There may be opportunity again to use it advantageously in SSOC.

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## Conflict Avoidance via Patterned Social Interaction

Another broad approach to avoidance of conflict in SSOC entails intentional structuring or channeling of social interaction among crew members. In particular, NASA might (a) design the supervisory-control structure so that it detects and resolves conflict readily, (b) structure the interpersonal contact on board the Space Station to minimize the probability of conflict occurring, and (c) structure communication on board so that message-type maps into media-types in a way that lessens the probability of conflict. Each of these is discussed below.

### Conflict and the Supervisory-Control Structure

Usually it is better to prevent conflict before it arises than to attempt to resolve it after it has escalated. For this reason, when designing the onboard supervisory-control structure for SSOC, NASA may wish to include what are termed "boundary-spanning roles" (Adams, 1976; Wall, 1974; Katz and Kahn, 1966; Holmes et al., 1986). These are roles the occupants of which perform functions that link subgroups together. For instance, persons in boundary-spanning roles may communicate across groups on sensitive issues, or serve as representatives in decision-making that affects the relations between subgroups. Because the SSOC social system will contain several subgroups, the inclusion of boundary-spanning roles in the larger system may help to avoid conflict between groups and to resolve conflict should it occur.

In systems without boundary-spanning roles, one typical consequence of conflict is a reduction or cessation of communication between the parties. Any such reduction of communication would obviously be undesirable in SSOC. The use of boundary-spanning roles in SSOC may be a way of establishing -- and of keeping open -- channels between the nationality groups on board. In addition, occupants of boundary-spanning roles can also serve as negotiators with respect to points of contention between subgroups.

In sum, the use of boundary-spanning roles in SSOC may provide a mechanism for avoiding conflict. The research/design issues for NASA are exactly what boundary-spanning roles, if any, to include in SSOC, and how to interface these roles with the activities of the Space Station's Mission Commander and other administrators. One possibility in this regard is to design the role system such that persons who will serve as lieutenants to the Mission Commander will also function as boundary-spanners.

#### Conflict and Interpersonal Contact

A related research/design issue is how best to structure interpersonal contact among regular crew members to promote cohesive, non-polarizing relations among subgroups in SSOC.

Research on Earth-based systems suggests that NASA might reduce the probability of conflict between groups by assigning tasks to crew members

with an eye not just to getting work done, but also to promoting cooperative contact and interdependence among persons from different subgroups (Amir, 1969; Worchel et al., 1977, 1978; Deutsch, 1973; Worchel, 1986). For instance, NASA might assign tasks such that persons from different nationality groups work on an interdependent basis. Under such an arrangement, both Americans and Europeans would do EVA, both Japanese and Europeans would do payload operations (experiments), and so on. The situation to avoid is one where the Japanese do all the EVA, the Europeans do all the payload operations, the Americans do all the flying, etc. The key is to create task-interdependence and cross-linkages among nationality groups.

Another potential overlap is that between Astronaut Pilots and Payload Specialists. If there are only four or six Astronaut Pilots on board in SSOC, there may not be much opportunity for task overlap between these groups. If there are many Astronauts on board, however, tasks can be assigned to promote collaboration. Some Astronaut Pilots might be assigned to conduct payload experiments on an interdependent basis with Payload Specialists. Again, the objective is to create ties across subgroups.

Beyond task interaction, NASA may also find it possible to structure non-task activities among crew members in such a way as to develop ties across subgroup boundaries. Of course, most waking hours each day will be spent on tasks (12 hrs/day); crew members will have little time for non-task activities. Yet, non-task interaction may prove important in creating and maintaining positive attitudes and trust across subgroups, in

part because the size of the SSOC crew will preclude all members from interacting with one another in a task mode.

Some research on Earth-based systems shows that informal contact across subgroups is most effective in strengthening intergroup bonds when it is conducted on an equal-status basis (Amir, 1969, 1976; Norvell and Worchel, 1981). Exactly how to do this in SSOC is an open issue. For instance, it may be desirable to assign spatial living quarters to create cross-linkages among nationality groups. That is, assign some USA astronauts to sleep in the Japanese module and the European module, assign Japanese and European astronauts to one another's modules and to USA module, etc. Alternatively, it may prove desirable to have crew members of different subgroups eat together (this will not carry special meaning for Americans, but it may for the Europeans). How to structure informal contact in SSOC to strengthen intergroup bonds is an open research/design issue for NASA.

#### Conflict and Communication

The communication system on board the Space Station in SSOC will differ from that in IOC. The size of the SSOC communication network will be larger (i.e., contain more nodes) than that in IOC because the crew will be larger in size. Moreover, the total communication flow (number of messages sent) will be higher in SSOC, although the messages per crew member may remain about the same. Communication flows in SSOC will reflect the clustering of crew members into subgroups; flows will be higher within and lower between subgroups.

From the standpoint of conflict and conflict resolution, however, the most critical difference between IOC and SSOC will be the media of communication used. During IOC, when the Space Station will have a small crew housed in a single module, a significant proportion of communication will doubtless be face-to-face. In SSOC, with a larger crew dispersed in several modules, a smaller proportion of communication will be face-to-face and a larger proportion will occur via other media such as telephone and electronic (computer) mail. This will result naturally because SSOC crew members will have to communicate with others in remote locations in the Space Station.

The shift in communication media between IOC and SSOC may be important because the various media have different properties. Telephones and computers, for example, do not convey some types of information as fully as the face-to-face channel (Mehrabian, 1972). Face-to-face communication transmits linguistic, paralinguistic, kinesic and proxemic cues, while electronic (computer) mail transmits linguistic cues only (Connors et al., 1984; Danford et al., 1983; Hall, 1968). One important consequence is that non-face-to-face media carry less information about personal relations and feelings. Thus, in view of the SSOC system's potential for fractionating conflict, heavy use of non-face-to-face media in SSOC may produce undesirable consequences.

Computer-mediated communication is especially problematic in this regard. The effects of computer-mediated communication are not yet fully understood, but it is increasingly clear that this medium is good for some

purposes, poor for others. Computer conferencing tends, for instance, to increase equality of participation more than face-to-face conferencing (Johansen et al., 1979), which may improve the potential for circumspect consideration of issues. Electronic mail is not, however, a good medium by which to conduct bargaining or to resolve interpersonal conflict, because it can foster one-sided proclamations and policy statements couched in concepts not shared by participants. More generally, computer-mediated communication may be less effective than face-to-face communication for reaching consensus on issues where the "correct" answer is not obvious. In addition, research shows that use of computer-mediated communication sometimes leads to polarization and flaming (Kiesler, et al., 1984). Behavior of this type would be especially undesirable in SSOC, given the subgroup differentiation projected for the social system.

The burden placed on computer-mediated communications will increase in SSOC in the sense that failures to communicate adequately may have more serious consequences in SSOC than in IOC. Communication failures will assume higher criticality in SSOC due to the differentiated nature of the social system. To communicate across cultures is difficult enough via face-to-face interaction; to rely heavily on media that filter information in unpredictable ways will make the communication problem even worse.

Thus, a general research/design issue for NASA is how may the SSOC crew best use the communication media on board the Space Station to promote non-polarizing interpersonal contact and to create cross-linkages between members of subgroups.

At the least, NASA may wish to develop an "etiquette" regarding use of the various media on board. This may include not only rules for the use of media, but also rules regarding what types of messages are to be sent over which media. Some theorists have hypothesized a (statistical) interaction effect between media type and message type on communication effectiveness (Geller, 1980; Danford et al., 1983). In view of this, one approach to the SSOC communication problem is to seek a match between media and the type of message being sent (i.e., where "type" refers to message content coded from the standpoint of its functionality for the social system). That is, to achieve high communication effectiveness, send some types of messages by one channel, other types by other channels. To achieve such regulation, the Space Station will need norms specifying what types of messages are sent via computer mail, what types via telephone, and what types via face-to-face contact. The exact nature of these norms is an open issue.

#### Conflict Avoidance via Selection and Training

NASA has traditionally placed great emphasis on selection and training of its crews. Selection and training will continue to play an important part in IOC and SSOC Space Station operations. The potential for conflict in SSOC, however, implies that when NASA moves from IOC toward SSOC, it may wish to make some adjustments both in the criteria used to select crew members and in the content of Astronaut training. An important research/design question is what should be the nature of these changes.

## Crew Composition and Selection

Certain obvious shifts will occur in NASA crew selection activities from IOC to SSOC. First, the number of persons selected will increase, because NASA will be flying larger crews. Second, the skill-mix of persons selected will shift; compared with IOC, a larger proportion of crew members will be Payload Specialists, a smaller proportion Astronaut Pilots. Third, the nationality of persons on the Space Station will change, to include Japanese and Europeans.

Less self-evident is that, when moving from IOC to SSOC, NASA may find it necessary to change its crew selection criteria. To enhance integration of the SSOC social system, NASA may opt for crew members who, by virtue of their background, can serve as linking-pins across subgroups. For example, in SSOC there may be a premium on crew members who have a background of cross-cultural or international experience, or who are multi-lingual (e.g., NASA Astronauts who speak French, or who have lived in Japan). Alternatively, NASA may choose to "manufacture" persons with such backgrounds by, for example, having its pilots live in Europe or Japan for several years.

Another possible change concerns the personality profile of the idea Astronaut. In IOC, with small crew size, there will be a premium on persons who are high on interpersonal compatibility and who relate well to others. The concept of interpersonal compatibility, however, is more applicable to small groups of 6-8 than to larger groups of 20-30. Rarely does one find a group of 30 persons, all of whom are interpersonally

compatible. Thus, in SSOC, the emphasis on compatibility may fade and give way to other interpersonal skills, such as diplomacy. More generally, a research/design issue for NASA is to discover which personal attributes of crew members best serve to enhance linkages between subgroups in SSOC.

### Conflict and Crew Training

Astronauts from different countries and reared in different cultures will hold different expectations regarding patterns of social interaction. Although these may not affect the technical aspects of space flight, some will seriously affect interpersonal sentiments. For instance, respectful interpersonal treatment among the Japanese looks different from that among the Americans or the French. Without adequate preparation, misunderstandings will arise among crew members. NASA may wish to address the implications of this when training Astronauts for SSOC.

Emphasis throughout this section had been on avoidance of conflict. Even with the best preparation, however, some conflict will occur in SSOC. For this reason, NASA may wish to train crew members in conflict resolution techniques. When persons are under stress, some forms of communication and negotiation are more effective than others (Pruitt, 1981; Rubin and Brown, 1975). Useful conflict management skills in American society include: reflective listening, assertion skills, issue control, structured exchange regarding emotional aspects of a controversy, and collaborative problem solving (Bolton, 1979; Walton, 1969). Whether

these techniques will work in a cross-cultural context like the SSOC social system is an open issue. If they do work, NASA may wish to include them in its training regimen. Their use could increase crew's effectiveness in dealing with interpersonal disagreements when they arise on board the Space Station. In sum, an important research/design issue is exactly what conflict resolution skills should be taught to crew members.

#### COPING WITH ENVIRONMENTALLY-INDUCED CRISES

##### Crisis: A Definition

As used here, the term "crisis" refers to a circumstance in which something threatens to destroy or impair the social system on board the Space Station, and which therefore requires an immediate response from crew members (as well as from Mission Control) to assure the continued functioning of the system. Crises can be precipitated by many different events. For instance, crises might result if: (a) a sudden leak or air-loss occurs, causing the cabin pressure to decline sharply, (b) a sudden loss of power occurs, (c) a crew member becomes seriously ill, (d) some space debris collides with the Space Station, producing serious damage, (e) one of the bio-experiments on board goes awry, releasing pathogens or contaminants that pose a threat to humans, or (f) fire erupts on board the Space Station. This list is illustrative, not exhaustive.

Most of the events listed here are improbable, in the sense that they will occur only infrequently. However, the Space Station will operate in a perilous environment for a planned 25-30 years and, while the probability of a crisis on any given day may be low, the odds of avoiding

crises are much less favorable over the full span of 25-30 years. Although not inevitable, one or several crises are probable during the operational lifetime of the Space Station.

#### Normal Operating Mode vs. Crisis Operating Mode

The structure of many systems in nature is controlled by the manner in which the system might fail (von Neumann, 1966; Weinberg, 1975). In other words, natural systems often incorporate some precautionary measures to prevent failure, or at least to prevent a failure from being lethal. Social systems also display this characteristic, and they often cope with crisis and failure by having several distinct operating modes, such as "normal operating mode" vs. "crisis operating mode." In normal operating mode, when the environment is not disruptive, the social system conducts "business as usual." Human plans drive the action, and the emphasis is on productivity and performance. However, in crisis operating mode, when the social system responds to environmental threats, there is a shift in the social system's objective function. The predominant goal in crisis mode becomes that of assuring the very survival of the system, and activities are reorganized in terms of this goal. Environmental contingencies, not human plans, drive the action; persons in the system become more reactive and less proactive.

Most likely, the IOC and SSOC social systems will use several operating modes. They may even implement several distinct crisis operating modes, contingent upon whatever types of crises occur. Nevertheless, crisis management in SSOC probably will differ from that in

IOC, in part because the shift from normal mode to crisis mode will be more difficult to accomplish in SSOC than in IOC.

## Crisis Management

### Crisis Management in IOC

Crisis-management is never easy, but the characteristics of the IOC social system will equip it well to respond to crises when they arise. The small size and great homogeneity of the crew, the housing of the crew in a single habitat module, and the nature of the supervisory-control structure will enable the IOC system to switch quickly to crisis operating mode from normal operating mode. In IOC, crisis operating mode will (a) establish centralized control of crew activities, (b) assure adequate information flow among members, (c) create the potential for clear, consensual decision-making, (d) rapidly establish coordination among crew members, and (e) apply the greatest expertise available to the problem. In social systems, these are desirable features under emergency conditions.

The IOC's supervisory-control structure, assumed to be patterned after a hierarchical "military command model," will function fairly well during a crisis. Because command is centralized, the system will hold together and coordination of action will be attainable even under stress. The hierarchical structure will enable the IOC system to focus resources, restrict non-adaptive responses (such as argumentation or countermanding), and achieve an adequate level of communication among crew members. In

general, it can provide the high level of interpersonal organization needed to respond to crises.

#### Crisis Management in SSOC

The SSOC social system will have more resources than the IOC system to deal with crises. For example, its hardware may have better sensors to anticipate crisis-precipitating events before they happen, its expert-system software may provide more accurate diagnoses of problems, and its crew may include a greater mix of skills useful during crises. Nevertheless, crisis-management in SSOC will present its own problems. The incidence of crises may be higher in SSOC than in IOC, because there will be more things to go wrong. There will be more crew members to get sick, more area to get hit by space debris, more bio-experiments to blow up, more on-board hardware to malfunction, etc. Moreover, the organizational form of the SSOC social system will make it more difficult to respond adequately to crises. The SSOC system may have more difficulty switching from normal operating mode to crisis operating mode than the IOC system.

The SSOC social system will be larger, more complex, and more differentiated than IOC. Moreover, as noted above, supervisory-control and decision-making in SSOC will be decentralized in normal operating mode. The presence of different nationality groups and of many Payload Specialists performing diverse tasks will create a heterarchical supervisory-control structure. If a crisis arises, the supervisory-control structure in SSOC must coordinate the response of

distinct subgroups living in different physical modules and pursuing divergent goals. This task is not impossible, but it will be more difficult than in IOC.

In all likelihood, a shift from normal operating mode to crisis operating mode in SSOC will entail a quick move from a decentralized heterarchical structure to a centralized hierarchical one. Failure to move back to a hierarchy during a crisis in SSOC will leave the system vulnerable. If the Space Station relied on a decentralized system during crisis, it would risk lack of coordination among crew members, less-than-optimal deployment of resources to deal with the problem, and perhaps even disagreement over the best type of response to the emergency.

Although a shift from heterarchy to hierarchy during crisis seems likely, the exact form of SSOC command during crises is an open research/design issue. Danford et al. (1983) have suggested that it would be appropriate to have control during crisis rest in the hands of a specialized safety officer or "crisis leader." This scheme has some merit, but it may also create excessive complexity because that it requires yet another form of control beyond the heterarchy-plus-Mission Commander structure discussed above. A superior alternative might be simply to recentralize control during a crisis around the regular leader (Mission Commander).

Recentralization around the Mission Commander will work best if NASA trains crew members in specific skills for dealing with different types of

crises. That is, some crew members will be specialists in coping with one type of crisis and other crew members with another type of crisis. Thus, when a crisis occurs, two things will happen. First, crew members will coordinate around the Mission Commander; and second, the Mission Commander, assisted by those persons who are specialists in the particular type of crisis at hand, will direct the efforts of the entire crew to cope with the emergency. This approach brings both special expertise and strengthened command to bear in a crisis.

A related research/design issue concerns the use of AI and computerization to aid decision-making during crises. Expert systems that diagnose the causes of hardware failures will be operational increasingly as the Space Station moves from IOC to SSOC, and these may increase the speed and accuracy of the crew's efforts during crises. To some degree, expert systems will be able to supplement (even supplant) the knowledge and expertise of crew members. On the other hand, use of AI systems in the analysis and diagnosis of life-threatening events raises the issue of trust -- to what extent will crew members trust software-based diagnoses. The use of AI may affect not only how the crew is organized to cope with crises, but also what mix of skills is (and is not) placed on board and how crew members are trained. These are matters that can be addressed through research and design efforts.

One final research/design issue concerns the impact of computer-mediated communication during crises. As noted above, computer-mediated communication will be even more important and prevalent in SSOC than in IOC. Whether computer-mediated communication enhances or

inhibits satisfactory responses to crises is an open question. It was noted above that computer-mediated communication may be less effective than face-to-face communication for reaching consensus on issues where the "correct" answer is not obvious. Some crises on board the Space Station may have clear-cut diagnoses, but for those that do not, computer-mediated communication may prove more a liability than an asset in achieving adequate response from the crew. The (in)effectiveness of computer-mediated communication during crises is an important research topic.

#### SUMMARY OF RESEARCH AND DESIGN ISSUES

This paper has discussed issues that arise in the design of the SSOC social system. Attention has been given to three broad problem areas: (a) the characteristics of the SSOC supervisory-control structure, (b) the potential for conflict within the crew, and (c) the capacity of the SSOC system to respond to crises if they arise. Specific research suggestions are summarized below.

#### Issues Regarding SSOC Supervisory-Control

One important research/design issue for NASA is what type of supervisory-control structure will best serve the SSOC social system, in the sense of providing the greatest efficiency and highest probability of mission success. There are a wide variety of supervisory-control structures that might be deployed on board the Space Station --

hierarchical, equalitarian, heterarchical, etc. -- and the exact nature of the system to be used is an open issue.

It has been proposed here that the Space Station's supervisory-control structure will take the form of a hierarchy in IOC, and that it may subsequently shift in the direction of a heterarchy in SSOC. This is really no more than a conjecture, however. NASA can make decisions regarding the form of supervisory-control structure to be used in IOC and SSOC on the basis of trial-and-error or past experience with space flight supervision. Alternatively, it might make them on the basis of research findings, such as those obtainable from simulations conducted on the ground.

Specifically, it was suggested above that NASA might conduct simulations to test various outcomes from different supervisory-control structures. These simulations would be done under conditions that closely replicate those found in space -- e.g., high stress, high noise, restricted communication, 90-day duration, tasks similar to those done in space, and so on. Major outcome measures include productivity levels, crew satisfaction, lack of conflict, adequacy of response to emergencies, etc. Multiple replications could be run on each of several alternative supervisory-control structures using experimental designs. The results should provide a useful indication of how the alternative supervisory-control structures will perform in space.

One design sub-problem is to determine the appropriate division of control between Space Station crew and Mission Control on Earth. One

concrete manifestation of this problem is the issue of who should have control over the crew's day-to-day task assignments. Various suggestions, including the use of AI project planning software to accomplish task assignments, were discussed.

A second design sub-problem is to determine the appropriate division of control within the Space Station's crew. Presumably the Task Specialists in SSOC will be afforded some degree of independence with regard to their particular activities, but the exact range is unclear. The Mission Commander's role during SSOC will likely shift toward coordination of other's activities, but the exact definition of the role's prerogatives and powers is problematic.

A related issue is the selection criteria regarding crew officers; this matter is made more complex by the inclusion of crew members from other space agencies (Japan, Europe). Whether the role of Mission Commander will be restricted to NASA Astronauts or open to crew members from other countries is a research/design issue that NASA might address.

#### Issues Regarding Crew Conflict in SSOC

The risks of interpersonal and intergroup conflict will be greater in SSOC than in IOC. This is true in part because the SSOC system will include many subgroups with distinct identities (Task Specialists/Astronauts; and USA/Japan/Europe). The broad research/design question for NASA is what safeguards to build into the SSOC system to

reduce the probability of overt conflict occurring, and to resolve conflict if it occurs.

A wide variety of steps can be taken in the design of the SSOC system to reduce the probability of conflict. Some discussed in this paper include:

(a) Specify objective function(s) for the SSOC crew such that the attainment of goals by one subgroup does not prevent the attainment of goals by other subgroup(s). Approaches to this include the use of superordinate goals and game-theoretic analysis of subgroup interaction. One implementation might involve computer software (project scheduler routines) to optimize not just productivity but also group overlap.

(b) Incorporate boundary-spanning roles in the SSOC social system. An open question is how to interface these roles with the activities of the Space Station's Mission Commander and other officers.

(c) Structure interpersonal contact among crew members to promote cohesive, non-polarizing relations across the subgroups in SSOC. Crew members might be assigned tasks with an eye to creating interdependence and cross-linkages between nationality groups. Likewise, module living and sleeping assignments might be made to promote contact across nationality groups.

(d) Use of the communication media on board the Space Station to promote non-polarizing interpersonal contact and cross-linkages between

members of subgroups. Computer-mediated communication is especially problematic in this respect, for it may worsen, not improve, the prospects for intergroup conflict. NASA may wish to develop some rules or "etiquette" regarding use of computers for communication.

(e) When moving from IOC toward SSOC, NASA may need to make some adjustments in the criteria used to select crew members and in the content of Astronaut training. In this regard, a research/design issue for NASA is to discover which personal attributes of crew members best serve to enhance linkages between subgroups in SSOC. Another issue is to determine what conflict resolution skills should be taught to crew members.

#### Issues Regarding Response to Crises in SSOC

The SSOC social system may have more difficulty than the IOC system in mobilizing to deal with various crises and emergencies on board. This will occur not only because SSOC is a larger system, but also because it is more heterarchical in form with decentralized decision-making. The broad research/design question for NASA is how best to structure the SSOC social system so that it can mobilize adequately for crises. Some writers have suggested placing control during crises in the hands of a specialized safety officer or "crisis leader." This proposal has some merit, but a better alternative may be to recentralize control around the regular Mission Commander. NASA may wish to investigate this research/design issue more closely.

Moreover, NASA might investigate the use of AI expert systems to help deal with crises -- the software system becomes the crisis advisor, assisting or even supplanting human decision-making. Use of expert systems in this context may improve diagnosis of the problem, as well as increase speed and accuracy of response to the emergency.

Finally, NASA may wish to investigate the (in)effectiveness of computer-mediated communication during crises. Whether computer-mediated communication enhances or inhibits responses to crises is an open question. Some crises on board the Space Station may have clear-cut diagnoses, but for those that do not, computer-mediated communication may prevent or diminish an adequate response from the crew. The effects of computer-mediation on communication during crises merits scrutiny.

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CONFLICT AND STRESS IN THE SPACE STATION:

A COMMENTARY ON THE

MICHENER AND COOK PAPERS

Oscar Grusky

Department of Sociology  
University of California  
Los Angeles, California

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CONFLICT AND STRESS IN THE SPACE STATION:  
A COMMENTARY ON THE MICHENER AND COOK PAPERS

The primary question both Michener and Cook's papers are concerned with is the impact of social factors on the performance of human groups in manned vehicles in space missions of long duration. My comments first address some issues raised by Michener. Then I turn to selected portions of Cook's paper. Finally, I make some general observations and conclude by arguing that a need exists for a systematic data base on social system processes based on past long duration space flights.

COMMENTS ON MICHENER'S PAPER

The theme of Michener's paper is the impact of social system factors on the management of system conflict. He asserts that as crew size increases, crew composition becomes more varied, system goals become more complex and diverse and onboard artificial intelligence and computerization increases, the likelihood of control and conflict problems will become greater because of social system failures. Such failures come about in part because of the greater complexity, differentiation, and decentralization that is created by changes in crew size and composition, technology, and goals.

As Michener notes, the space station crews confront a perilous environment and one that they must deal with largely on their own (Michener does not mention but is no doubt cognizant of the fact that under the current design there is no way a crew member can return to earth

in an emergency, since there is no escape vehicle), relative isolation, and a long period of time in space, i.e. 90 days. The SSOC system will have to deal with very complex supervisory control problems, the risk of intergroup conflict, and the necessity of coping with serious crises.

One contributing cause of conflict in the space station, according to Michener's analysis, is modularity. Modularity refers to a social system composed of multiple and distinct subgroups. Michener claims that modular systems may be particularly vulnerable to conflict, miscoordination, lack of cooperation, and mistrust.

Because space station must function in such a perilous environment it is vulnerable to the risk of exogenous shock, that is, an uncontrollable event. More complex social systems are presumably less capable than less complex social systems of coping with such exogenous shocks.

Naturally, one of the first questions one asks when confronting a theory such as this is how does it square with the available evidence, realizing that most evidence is earth-based and therefore only partially relevant or relevant to an indeterminate degree. There is, however, additional evidence, also of limited or of indeterminate value, that may be obtained from observations on group performance in long duration space flights that have already been undertaken. Unquestionably, there is a need for additional systematic research on the problems of group conflict and performance in the space station.

## Effects of Group Size and Complexity

Michener suggests that SSOC is likely to experience greater conflict than earlier missions, in part, because the social system will be larger and more complex. However, the evidence on the effects of group size is not uniform. There is no doubt that as group size increases the potential number of intragroup relations multiplies. But the effects of group size on factors such as member commitment, cooperation, and group performance are unclear. For example, Michener suggests that larger-sized groups have weaker member commitment than smaller-sized ones. However, Doll and Gundersen (1969) studied Antarctic groups and found that perceptions of members of compatibility were more favorable in larger (size 20 to 30 members) than smaller groups (size 8 to 11). More recently, Yamagishi (1986) studied laboratory-created groups of size 2, 6, 11, 51 and 501 in order to study social dilemma or public good situations.<sup>1</sup> Subjects were told they would be given \$5 and would be asked to give any number (0 to 5) of one dollar bills to others in the group (group condition) or to matched participants (give-away condition). Yamagishi found that once group size exceeded ten, additional size increases had no effect on member contribution level. The point is that earth-based studies of the effects of group size on both utilitarian and affiliative type group goals have not produced uniform findings.

### Conflict

Michener is not specific about the causes of conflict, but the close interactional situation in the space station provides the potential for

seemingly minor events to stimulate interpersonal hostility. For example, there is waiting to gain access to the toilet. It takes longer to use zero-g facilities and space constraints will mean a limited number of toilets. Hence, long waits especially when waking up may be common, and questions of priority may produce conflict.

As Michener points out, since no large social system has been established in space, there are no alternatives but to develop generalizations based on earth-based groups. However, potentially suggestive information may also come from extrapolating from observations on smaller-sized groups that have been in space, such as Skylab. Pogue, (1985) a Skylab astronaut who spent 84 days in space, has written a book describing some of his experiences. Two others accompanied Pogue on his long mission, the Commander (Carr) and the Scientist Pilot (Gibson). Pogue reported that overall the crew got along well together and that they had so many equipment problems that they "had to help each other often. We had good team spirit." Very little space in his book was devoted to the subject of interpersonal conflict. In response to a question on fights and arguments among the crew, he observed: "We didn't have any fights, and there was only one argument that I can recall. It had to do with a change in procedure, and the instructions were very vague. We resolved this by trying the procedure to see if it worked. We never got truly angry at each other, but we were frequently upset with or had disagreements with some people in Mission control. We were all trying hard to get a job done, so there was probably fault on both sides at one time or another" (Pogue, 1985:67). These comments suggest first, that the crew was reasonably well-integrated and supportive of one another, and

second, that group identification was to some extent strengthened as a product of antagonism toward Mission Control.

Pogue recounts only one incident that took place between him and the Scientist Pilot that could be characterized as a disagreement: "I think I upset Ed Gibson one day by putting his ice cream in the food warmer and leaving his steak in the freezer. I really felt badly about it. He couldn't eat the steak because it was still frozen hard, and the ice cream had turned to milk. He had to dig out some contingency food to eat. There wasn't too much conversation at dinner that night. He salvaged the ice cream by refreezing it. In liquid form it had turned into a big hollow ball. The next day, after it refroze, he stuffed it full of freeze-dried strawberries and had the first strawberry sundae in space" (Pogue, 1985:67). Attention to these comments is called mainly to suggest the need for collecting and analyzing systematically social system data on conflict already collected from long duration missions, such as Skylab and Salyut. Analysis of these data may help in identifying potential social system sources of conflict on space station. The Russians have had a small space station, Salyut 7, in orbit for almost five years and have manned that station periodically since then. About a year ago they launched the first element of a modular station which is designed to be permanently manned. Bluth (1984) has reported on Soviet evidence of strong interpersonal hostilities among the crew on the Salyut missions.

## Mission Length, Conflict, and Expectations

As Michener notes, the projected length of space station missions is 90 days. Another reason for carefully examining group factors in the Carr-Gibson-Pogue Skylab mission is that its length was 84 days or almost the same as the proposed space station missions. As noted above, the Russians also have completed long duration missions that are of interest. Their experience with such missions exceeds ours. Michener argues that the long length of the space station missions may lower crew tolerance and encourage greater subgroup conflict. However, Pogue (1985) and the New Yorker report (Cooper, 1976)<sup>2</sup> both note that mission length did not constitute a problem on Skylab in the sense of elevating interpersonal tension. The crew apparently did get very disturbed when Mission Control proposed near the end of the mission the idea of lengthening it. It appeared that two factors contributed to the crew's strong dissatisfaction with this idea. First, the crew was trained and geared from the start for an 84 day mission. They had prepared themselves both mentally and physically with this period of time in mind. Hence, a proposed change in the schedule greatly upset their expectations and was dissonance-arousing. Second, and relatedly, the very fact that it was raised as an issue by Mission Control at the crucial point in the mission may have seriously undermined the crew's sense of personal control over their actions. These were very proud and extremely capable individuals with a strong sense of personal autonomy. The tight daily scheduling of their actions and the close observation and monitoring of even minute aspects of their behavior over a long period of time may have been threatening and stress-arousing to these competent and autonomous

individuals. The composition of these groups and their training was designed to mute social system conflict, promote strong group integration, and strengthen identification with the group goal or mission. However, such strong identification with the group goal may inhibit externally-induced changes in the mission. Presumably any such changes, if group resistance is to be avoided, must involve a participative process worked out in advance.

In addition to this issue of whether or not greater size and differentiation actually contribute to greater group conflict, there is the matter of the consequences of such conflict for group functioning, and in particular, productivity. Michener assumes that conflict will increase with greater differentiation and complexity, and furthermore, that conflict in general is detrimental to group performance. There is not a great deal of evidence on this, and what exists, is earth-based. Michener, like most students of conflict, sees conflict as creating disequilibrium in the system. Conflict may cause a "breakdown in decision making" (March and Simon, 1958), that is, it is a malfunction and is negatively valued. However, other social scientists, such as Coser (1966) look at certain kinds of conflict as a source of equilibrium and stability. Coser argues that a multiplicity of small conflicts internal to a group may breed solidarity provided that the conflicts do not divide the group along the same axis, because the conflict coalitions provide a place for exchanging dissenting opinions. In essence, he claims that some conflict or disagreement is inevitable and that it is better to foster minor conflicts of interest and thereby gradually adjust the system, than to allow for the accumulation of many latent deep antagonisms that could

completely disrupt it. Coser notes that frequent small conflicts keep antagonists informed of each other's position and strength and hence prevent a serious miscalculation on the part of either party. In a similar vein, Lipset et al. (1956) in a study of the International Typographer's Union showed how institutionally-regulated conflict between the two political parties in the union actually fostered a democratic climate and organizational stability. Likewise conflict between modules may take the form of healthy competition and this may enhance overall productivity. Thus, conflict and competition are not inherently dysfunctional as Michener suggests. Contrary to Michener's approach, this perspective suggests that a key issue is not merely how much conflict takes place, but the conditions under which conflict occurs, for example, the extent to which it is normatively regulated and controlled.

#### Crew Rotation

Michener mentions only briefly that rotating crews under extended duration space flight may effect their functioning. The effects of rotation, succession, or turnover, merits more detailed treatment. There is a substantial literature on this topic concerning the effects of rate of succession on group and managerial effectiveness (e.g. See Grusky, 1963, 1964; Brown, 1982). Practical research questions include: optimal mission length, optimal method of crew rotation (replace individuals, subgroups, or total crews), optimal method of leader rotation, etc.

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COMMENTS ON COOK'S PAPER

Cook's paper is concerned first of all with stress and the relationship between stress and productivity. In addition, she examines the issue of mediated communication, particularly computer-mediated communication and its effects on productivity.

Stress

Cook proposes that space be used as a site for basic research on stress. She points out that reliable and valid non-physical health-related measures of stress are lacking. Space station is a good site for stress research, she claims, because there are so many stressors in space, such as crowding, noise, workload, and life-threatening crises. She describes a model of stress produced by interpersonal factors such as inequitable assignment of rewards, task or role ambiguity, arbitrary exercise of authority, and others. Cook wishes to complement physiological and psychological stress research by investigating social system properties of stress, an approach that has not been heavily utilized in the past. She also wants to explore adaptive group strategies for coping with stress. She proposes the intriguing idea of developing a computer-aided system to rectify cognitive processing deficiencies that appear under high stress levels. However, one of the problems with stress measurement is that so many factors can be stressful that objective quantitative measurement is difficult.

## Gender and Stress

Although up to the present space missions have been male-dominated, it is evident that future missions will involve more female astronauts and mission specialists. Research in psychiatric epidemiology has consistently documented an association between gender and psychological distress. Women are more than twice as likely as men to report affective disorders and extreme levels of distress (Al-Issa, 1982; Kessler and McRae, 1981). Although male prevalence of some psychiatric disorders is greater than females and for some disorders there is no reported association with gender, the best available evidence indicates that the psychological well-being of women is different than that of men.

The major sociological interpretation of this evidence is that women's roles expose them to greater stress than men's (Gove, 1978). Gove (1972) has claimed that female role stress is especially pronounced in traditional role situations.

A number of investigators have shown that women are more vulnerable than men to a range of what have been called network events, that is life crises that are significant to the lives of persons important to the respondent (Kessler, 1979; Radloff and Rae, 1981). Kessler has proposed that women care more about people, and because this is the case, they are more vulnerable to crises that take place "at the edges of their caring networks." (Kessler, 1985). Men are emotionally affected by crises that occur within their nuclear family, but women are more deeply affected by

both crises among members of their nuclear family and among persons who may be classified as friends and associates.

There are a number of major limitations in the analysis presented above:

1. The findings showing a relationship between gender and psychiatric distress and subclinical distress can be explained by selection factors.
2. Most of the evidence on role-related stresses has been based on scales using subjective evaluations.
3. Evidence on the differences suggested between men and women claiming that the latter are more vulnerable to crises in their networks is sparse.

Despite these limitations of which Cook is well aware, this information and the speculations described above raise some potentially important issues regarding long duration space missions. Specifically, one issue is whether or not male and female crew members will take on different roles and respond differently to crises that may take place in the space station. Kanter (1977) has studied the lone woman in male-dominated work organizations as part of her study of what she calls "skewed sex ratios." She has distinguished between dominants and tokens in these organizations and suggests that (1) tokens are more visible than dominants (2) differences between dominants and tokens tend to be

polarized and (3) tokens' attributes tend to be "distorted to fit pre-existing generalizations about their social type." At issue is the effect (if any) of the gender distribution in the group on command, control, and communication processes. It may very well be the case that selection factors that have up to now worked well in identifying crew members capable of handling stress will continue to work effectively in the future. It is also reasonable to anticipate that besides selection effects, situational effects will be overpowering and hence the gender differences suggested above will be masked. Alternatively, it may be that the larger-sized groups in space station 1990s combined with the existence of a "skewed sex ratio" (Kanter, 1977) in work groups will have problematic impacts on group functioning. Research is needed to explore these and related issues.

#### Computer-Mediated Communication

As Cook has observed, the social consequences for systems of long duration where the primary communications are computer-mediated are simply unknown. As Cook notes, the recent finding by Siegel et al. (1986) that computer-mediated communication facilitates the upward flow of negative communications or information that challenges those in high status positions merits replication. This problem also should be studied developmentally to see if changes occur as groups exist over long periods of time. Another related problem that merits study is the potential impact of cultural differences on computer mediated communication. People of different cultural backgrounds may respond in radically different ways. Such differences if found could be consequential to communication

between the various space station modules, the Japanese, European, and that of the United States.

Cook cites Connors (1985:32) research as justification for the proposition that "computer mediation may mitigate the inhibiting effects of face-to-face communication when "subordinates" have access to critical information and may need to challenge authority." However, Connors' groups bear little resemblance to the environment experienced by past long duration space flights or presumably will be faced by future flight crews, such as weightlessness, continuous peril and public exposure, continuous high task-load, small amounts of space per person, etc. Moreover, the idea of challenging authority and attitudes toward work are culture-bound. Hence, even if the findings were applicable to the United States' space module, they would not necessarily be as applicable to the Japanese or European modules.

#### CONCLUDING COMMENTS

Most of the comments in the two papers focus on negative effects such as conflict, stress and miscommunication. Michener stresses the perilous environment, the possibility of conflict between modules, human error possibilities, and breakdown possibilities that stem from the sophistication of the technology. Michener neglects the potential positive contributions of small conflicts and competition to group functioning providing that such conflict and competition is institutionalized and is expressed in legitimate ways. Cook focuses on the problems of decisional and interpersonal stress. Yet, in contrast,

what was highlighted in the narrative reports, both by Pogue (1985) and The New Yorker (Cooper, 1976) accounts, was the relatively smoothness of interpersonal relations among the Skylab crews, their high motivation, high productivity, high goal identification, and group commitment. Perhaps these reports have been "sanitized". In any case, it is clear that the social system impacts with respect to conflict and stress are unknown, although we do know that these factors can have consequential effects, and as Michener suggests, increasing social system complexity may enhance the likelihood of social system problems.

Both the Cook and the Michener papers stress the importance of social organizational factors on productivity or performance. Cook calls attention to the work of Foushee (1984) who has used flight simulators to study group process. Foushee cites a study by Ruffell Smith (1979) who had B-747 crews fly a simulated flight from New York to London. A failed engine, hydraulic system failure, poor weather, and other problems created an emergency situation. Foushee observes significantly that "Perhaps the most salient aspects of this flight simulation study was the finding that the majority of problems were related to breakdowns in crew coordination, not to a lack of technical knowledge and skill." Research on social factors affecting group conflict, stress and other related issues as both Michener and Cook have observed, is essential.

In summary, four major observations were made on Michener's paper, as follows:

1. Findings from earth-based laboratory and field research on the effects of group size and complexity on task performance have produced inconsistent results.
2. Michener's social system theory suggests considerable potential for group conflict on the space station. However, narrative accounts describing a Skylab mission do not conform to this theory.
3. Michener's theory assumes that conflict and competition (seen as a form of conflict) has only deleterious consequences for social systems and this may not be the case when conflict is institutionally regulated.
4. Michener omits extensive discussion of problems associated with crew rotation.

The following observations were made on Cook's paper:

1. The development of new methods of measuring stress and coping techniques are needed. Existing data on Skylab crew behavior should be examined in order to identify effective interpersonal coping strategies, that is, techniques that crew members have used that reduced, controlled, or made stress more tolerable.
2. Research is needed to explore systematically the relationship between gender, group structure, and stress.

3. Research is needed on the social impacts of computer-mediated communication. We need to know the positive and negative consequences of computer-mediated communication for individual and group decision processes. Cook has identified a set of hypotheses that merit intensive study.

Some of these problems can best be studied by means of human simulations where the space station situation is simulated in the laboratory by means of a mock-up and human crews of eight to ten or even twenty volunteer subjects are studied continuously in the laboratory for long periods of time. The crews would be given carefully assigned tasks as similar as possible to those to be performed by space station crews. The noise level is manipulated as are living conditions to approximate as closely as possible the real situation. Ideally, one would develop a set of experimental studies using the simulation method which would enable the close study of the effects of key independent variables such as authority structure on crew productivity, performance, and satisfaction. The same technique could be employed to examine the effects of various methods of crew and leader rotation.

A fundamental research recommendation should be added to those noted by Michener and Cook, namely the need for development of a systematic data base in the area of group performance of past (and future) astronauts in long duration space missions. Such a data base is especially needed because the space station is a unique environment due to the interaction of a very unusual set of characteristics such as weightlessness, constant danger, restricted or computer-mediated communications, high stress due to

noise, and other environmental hazards. Valuable although limited information can be obtained from studies of social systems facing quite different but presumably comparable situations such as polar environments and long duration submarine missions. Hence, there is a great need for data on this particular type of social system that is unique to long duration space missions. The types of data that should be included in such a data base are demographic information on the astronauts, performance data, and perhaps most important of all, audio and videotapes of missions, such as the three-person Skylab missions discussed above. Research access to these tapes would facilitate development of new measures of stress and conflict and their relationship to decision processes and would permit study of microgroup processes such as initiation of interaction, rates of interaction, and measures of power (such as interruptions, talkovers, and overlaps, etc.). The hope is that NASA might be convinced that a data base of this kind would be a valuable research resource for them and that such a data base could be assembled and the data analyzed in such a manner as to conceal appropriately as necessary the identities of particular astronauts and their specific missions.

## NOTES

1. Obviously Yamagishi did not create actual groups with 501 members in the laboratory. Instead, he allowed no communication or contact between subjects, who were isolated from one another, and told them the number of persons in their "group". No data were presented on the validity of this manipulation.
2. The New Yorker account also suggested that the three-person Skylab crews varied substantially in their productivity. One major determinant of this variation was how much was demanded of them by Mission Control. When a point was reached that seemed to the members of the crew to overtax their capacity, they complained and Mission Control reduced the workload.

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SESSION 6:

SOCIAL FACTORS IN PRODUCTIVITY & PERFORMANCE

SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

Oscar Grusky

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SOCIAL FACTORS IN PRODUCTIVITY & PERFORMANCE  
SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

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Due to time limitations only a brief discussion of the papers in this session was possible. Two main comments on these papers were made, as follows:

1. It was pointed out that neither of the papers considered the relationship between the airborne or space station crew and the larger community that participates in the operation of the station. The role of mission control, for example, was not mentioned and merits careful examination. The airborne crew does not exist in isolation and reflects the objectives of the larger organization and of the nation (or nations) as a whole. Mission control is in constant communication contact with the airborne crew and serves important functions with regard to its safe, effective, and efficient operation.
2. It was suggested that the extant literature on social system behavior in a number of other analogous "hostile" environments such as undersea or in Antarctica be reviewed carefully for information that might be relevant to the situation of long-duration space missions.

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SESSION 7:

THE HUMAN ROLE IN SPACE SYSTEMS

Paper: David Akin, MIT

Paper: William Starbuck, New York University

Discussant: Harry L. Wolbers, McDonnell Douglas

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THE ROLES OF HUMANS AND MACHINES IN SPACE

David L. Akin

Space Systems Laboratory  
Department of Aeronautics and Astronautics  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

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## INTRODUCTION

Throughout the history of the space program, there has been a dichotomy of opinions on the relative importance of manned and unmanned (i.e., robotic) applications. Until the arrival of the shuttle, manned and unmanned operations occupied different sections of NASA Headquarters, involved different groups of NASA field centers, and were generally viewed as competing for the limited funds available. There were (and still are) areas, such as planetary exploration, where there were no viable options to the use of unmanned systems. The arguments, rather, tended to the utility of humans in space, and the cost of replacing each of their functions with robotic alternatives.

Any self-contained device performing a useful function in space, whether a human or a robot, must contain the same set of basic functions to adequately perform the mission. In many cases, of course, the mission is actually constrained to work around the limitation of the state-of-the-art in one or more of these areas. These basic functions for autonomy include:

**Sensation**      In order to operate on the local environment, a system requires sensors for detecting objects. These typically break down into remote sensors (such as vision or other ranging systems) and proximal (such as tactile and force sensors).

Computation Having the capability to detect objects does not translate directly into the capability for manipulation.

Understanding the spatial relationships, having a knowledge base of both general activities (tools, forces and motions) as well as specific knowledge (specific satellite design details) are necessary for effecting a complete system.

Manipulation This area has trailed the others considerably, as many of the original space objectives did not involve manipulative activities. Manipulation to date has been performed by the sampling arms of the Surveyor and Viking landing spacecraft in small scale, and by the Remote Manipulator System of the shuttle in larger scale. None of these systems has involved any appreciable dexterity in either the arms or the end effectors. Nonetheless, this area is pivotal for future space activities, as it relates to the capability of the spacecraft system to interact with, and to alter, its local environment.

Locomotion This is a necessary function, often relegated to a supporting role. The capability to maneuver around in space, either on an existing structure or in free space, is required for any robotic system to be generally useful. It might be anticipated that space systems will evolve a wider range of locomotive capabilities than humans have evolved in a gravity field. For example, legs on a human provide both locomotion and anchoring functions. In the microgravity

environment of space, locomotion might well be relegated to the equivalent of arms, which have the finer dexterity and force control required in the absence of damping, and anchoring left to sets of specialized manipulators with strength, but little other capability. Thrusters for free-flight propulsion will also be common, at least for those situations not constrained to minimize use of consumables.

Support This category includes all the other functions necessary for the system to exist. This would include power, cooling, structural integration, navigation, and communications.

It is interesting to examine a known autonomous system (a human) in the context of these functions. The head is the sensor platform, located in the optimal location for bipedal locomotion. The computational system (brain) is co-located with the sensors in the head; to minimize the length (and vulnerability) of the high-bandwidth data paths, particularly vision. The arms form a dexterous manipulative system, and the legs similarly perform locomotion tasks. The torso thus encompasses most of the support functions, as well as tying all of the other systems together in a self-contained unit. The human body is thus a wonderful example of a possible design for a robot. However, the human paradigm should not be extended too far, as many of the optimal choices for a system which stands erect in a gravity field may have little logical application in a system optimized for weightlessness.

The task, therefore, is to come to an understanding of the past and present roles of humans and machines in space activities, and extrapolate to the future to come to a meaningful understanding of the capabilities and limitations of each. In fact, it is worth emphasizing at this point an essential conclusion of this paper: it is not an "either-or" choice between humans and machines. There are necessary and sufficient roles for both in the foreseeable future in space.

#### HISTORICAL PERSPECTIVES FROM SPACE FLIGHT

With the limited payload capability of early launch systems, there was no viable alternative to the use of unmanned satellites. These early payloads were composed of sensor packages, communications gear, and support systems, and were required to do nothing more than observe/measure and report their findings. Even today, many of the satellites being launched to orbit are still limited to these functions; for the purposes of this paper, these systems may be considered to be subrobotic systems.

It seems clear that the original intention of the Mercury program was to use the humans as an experimental subject, in order to study the effects of spaceflight on humans. The choice of experienced military test pilots for Mercury astronauts led to some predictable dissatisfaction with this role, and the desire for incorporation of manual control capability in the vehicle. This led to the use of the human as a controller, albeit primarily in the backup mode. A case in point was the Mercury attitude control system. The primary system was an automatic one, which maintained the capsule in retrofire attitude during orbital operations. A second

selection was "fly-by-wire", in which the astronaut could command attitude maneuvers by use of a side-stick controller, which would then be performed by the attitude control system. The final mode, however, was purely manual, as the astronaut actuated push-pull rods which mechanically opened and closed thruster valves.

This issue of humans as the final back-up is a pivotal one. For example, Mercury was a simple spacecraft, designed primarily for a single, sequentially organized mission. It carried no on-board computer, but instead relied on activating systems at set times on a mission clock. Contingencies, such as the decision to enter without jettisoning the retropack on John Glenn's orbital mission, relied on manual activation of retrofire commands to prevent the sequencer from automatically separating the retropack following retrofire. Thus, throughout the Mercury program, the human represented the adaptable (reconfigurable) element of the Mercury control system.

The Gemini program was an interesting "backwater" of space flight development. Originally conceived as a Mark II version of the Mercury capsule, Gemini was developed as an interim program to increase space flight experience while waiting for the development of the Apollo system. Since it represented to some an evolutionary dead-end in manned space flight, the manned elements were permitted to have unusual sway in the systems development. Thus, where Mercury was largely automatic, Gemini was almost entirely manual. It might indeed be argued that, more so than any other space program before or since (including Shuttle), Gemini was a pilot's spacecraft. There were no automatic abort modes: the crew had to

decide the appropriate action based on the reports of the instruments. For the first time, a space vehicle could be accurately described as a spacecraft, since Gemini had the capability to change orbits and achieve rendezvous. The crew had windows which faced forward, and hatches which could be opened and closed again in flight. Even in landing, the vehicle was positioned to allow the crew to sit upright, and much development effort took place towards a Rogallo-wing recovery system which would have allowed Gemini to maneuver to a landing on the dry lake bed at Edwards Air Force Base.

Even in the midst of this manual spacecraft, additional elements of automation had to be incorporated. The Gemini was the first spacecraft to fly with an on-board computer, used for calculating rendezvous maneuvers and for control of the lifting reentry. Although many of the procedures used for rendezvous and docking were manual in nature, the complexities of orbital mechanics required the use of ground or on-board computer calculations; the crew were primarily used as interpreters of visual and radar data.

The presence of humans on board Apollo may be considered as entirely a political decision, as the entire objective of the Apollo program was to place a man on the moon and safely return him to earth. The greater complexities of the spacecraft and mission led to a return to automated systems, after the largely manual nature of the Gemini spacecraft. Thus, for example, many of the abort modes were automatically initiated, although the crew did agitate for manual control of launch vehicle trajectory as a backup for the Saturn flight control system. The manual

docking techniques developed during Gemini were utilized by Apollo in lunar orbit.

Apollo again showed the utility of humans as a robust backup system. It was not possible to do a survey of landing sites down to the level of all possible hazards to the Lunar Module; it was therefore planned that the pilot would take over and steer the lunar lander to a safe landing site. This system worked well in every instance: the initial aim point for Apollo 11, for example, turned out to be right in the middle of a boulder field. Manual control of the landing vehicle allowed the targeting of landings next to an unmanned Surveyor spacecraft, adjacent to a deep lunar rille, and in the lunar highlands. This greatly augmented the data return, as later flights were targeted into areas of greater geological interest, with fewer options for safe landing sites.

The presence of humans to pilot the landers into safe locations may be compared to the Viking landings on Mars a few years later: since the unmanned vehicles did not have the image processing and decision making capabilities of humans, both of the landing craft had to be targeted to the flattest, smoothest, and therefore least interesting landing sites available. Similarly, the Soviet Union performed lunar exploration with unmanned vehicles. However, the quantity of samples returned differed from Apollo by 3-4 orders of magnitude; since the samples were selected randomly from the immediate location of the landing vehicle, it may be assumed that the quality of samples varied widely from Apollo as well.

Skylab, as the first American space station, involved the long-term habitation of space by humans. Indeed, one of the major objectives of Skylab was to study the effects of long-term space flight on human physiology; however, to use this objective as a justification for manned space flight constitutes circular logic. Much more may instead be said of the other science objectives of Skylab, such as earth resources, solar physics, and space operations. In all of these, the Skylab crews played an essential role in the success of the mission.

Since Skylab was constructed of surplus Apollo components, there was little significant difference between the two programs in the automation levels of the vehicle system themselves. The only significant difference was in the experiment packages, which in Skylab represented a later generation of technology from the spacecraft hardware. For example, the solar observing instruments in the Apollo Telescope Mount could be (and were) operated remotely from the ground. However, the onboard crewmen could provide more immediate decisions when faced with fast-breaking phenomena, and in fact managed to record solar flares from their inception. Modifications to the onboard control panel of these instruments during the course of the Skylab mission were primarily to increase the ability of the crew to make immediate data records for use onboard, by the addition of an instant-print scope camera.

Of greatest significance, perhaps, was the role played by the crew in the repair of the workshop and salvation of the mission. Extensive extravehicular activities (EVAs) were performed to free the jammed solar array, and to deploy a sunshade to reduce temperatures in the workshop to

habitable levels. The three Skylab crews regularly repaired failed equipment, both inside and outside of the space station, and clearly made possible the success of the program: had Skylab been an unmanned station with the state-of-the-art robotics of its time, it clearly would have had little or no recourse beyond those capabilities left by the launch accident.

The greater complexity of the Space Shuttle has led to the greatest amount of automation yet. Flight crews have referred to the Orbiter as the "electric airplane", since almost all functions are controlled through the four general-purpose computers (GPCs). The atmospheric flight characteristics of the Orbiter are such as to be practically unflyable without stability augmentation. Although a manual direct mode does exist, few of the flight crew have much success in this mode in training simulations, and even this mode relies on the GPCs to interpret hand controller data and command motions of the flight control surfaces. Although the flight control system is capable of flying the vehicle all the way through landing ("autoland"), it is interesting to note that no crew has yet allowed this to be tested on their mission: the commander always takes over in control stick steering mode (i.e., stability augmented) at subsonic transition, or certainly by the pre-flare maneuver at 2000 ft altitude. This is representative of many of the lessons learned from shuttle operations: the flight crew have now been cast in the role of systems managers, but still demand active involvement in all safety-critical aspects of the mission. It would be unwise to assume that this trend will not continue into the era of the space station.

## CAPABILITIES AND LIMITATIONS

It has been said that humans are the only self-programming, highly dexterous autonomous devices capable of being mass-produced by unskilled labor. Be that as it may, there are significant limitations on both humans and machines in the space environment. Having evolved in the environment of the earth's surface, it is necessary to (in some degree) take the conditions of earth along with humans in space. Constraints to be considered include atmosphere, consumables, volume, work cycles, and gravity.

Humans need oxygen above a partial pressure of approximately 3 psi in order to survive. Through the Apollo program, spacecraft were supplied with a pure oxygen atmosphere at 4 psi. This simplified several operational problems: the structures could be simpler, as the internal pressures were less; only a single gas had to be stored and delivered; and there was no requirement for denitrogenification prior to an extravehicular activity. However, the Apollo 1 fire showed graphically the primary disadvantage of a single-gas system.

In Skylab, the atmosphere was kept at 5 psi, with nitrogen forming the additional partial pressure beyond that required for oxygen. While this reduced the flame propagation problem, the crew was less than satisfied with the atmosphere, as it was difficult to carry on conversations beyond their immediate vicinity. Current plans for the Space Station assume a sea-level pressure of 14.7 psi, as used on the Orbiter. This decision is coupled into the choice of avionics: the sea-level pressure of the

Orbiter was partially chosen to allow the use of "off-the-shelf" air-cooled avionics. This had an effect on habitability, as the number of cooling fans on the Orbiter creates an appreciable amount of noise, thus limiting conversations to the immediate vicinity of the individuals. The Orbiter has been operated extensively at 10.2 psi during pre-breathe cycles prior to an EVA, but this requires a significant power-down of avionics to prevent overheating.

A biological organism, such as a human, is powered by a series of chemical reactions, and must be replenished regularly. In a totally open-loop system (that is, no attempt at recycling anything), humans will require approximately 5 kg/day of food, water, and oxygen. Recycling water and air will reduce this to 1 kg/person-day: this is equivalent to 540 kg of consumables for a six-person crew over a 90 day resupply cycle. Even without recycling, then, consumables are not a pacing item for a space station if the crew sizes are kept small. These figures also do not take into account such operational factors as air loss, inefficiencies in recycling, or food carried for reasons beyond base-level nutrition, and therefore the actual figures planned for consumables in space stations will be higher than these academic minimums. Many of the techniques for effective recycling are currently highly experimental, and will require a great deal of development prior to operational use.

Studies have shown a direct relationship between habitable volume and crew performance; the minimum volume is also a function of mission duration. In addition to the working volume, humans need to have shared facilities for eating, exercising, and personal hygiene, and are usually

best provided with some private locations for recreation and sleep. Deciding on these issues are some of the most difficult choices in interior station design, as there is often no clear relationship between productivity and volume; indeed, there is often no generally agreed-upon metric for productivity itself. Other desirable modifications to a spacecraft designed for long-term human occupancy include windows (as many and as large as the structural designers can be forced to incorporate), airlocks, and redundant escape paths in case of contingencies such as hull penetration or fire.

Humans are not capable of working "around the clock": some amount of recreation is required, along with natural housekeeping and other support functions and a sufficient amount of sleep. A normal 40 hr. week represents a 24% duty cycle for a human. Assuming five hours per day for meals, housekeeping, and exercise represents a further 21% of the time, leaving 55% of the day for sleep, recreation, and general off-duty activities. This may be compared to the averages for Skylab: 25.6% experiment operation (work), 33.9% meals, housekeeping, and exercise, and 40.5% for sleep, rest, and other. It is interesting that the net percentage of time spent on experiments is so close to that of a typical 40 hr. week; the exhaustive pace reported by the Skylab crews clearly demonstrates the increased overhead associated with living in space. Evidence indicates that the work pace established in Skylab would be difficult to maintain over indefinite periods on a space station: therefore, planners must either accept lower than normal duty cycles on experiments and other output-oriented activities, or plan ways of automating the housekeeping functions to bring these back in line (from a

perspective of time) with comparable activities associated with living on earth.

One of the origins of the increased housekeeping times is the necessity of adapting to routine living in the weightless environment. Although it can certainly be maintained that insufficient experience has yet been obtained to provide definitive conclusions in this area, clearly it will be difficult to overcome the millions of years of evolution in a gravity field in a brief time, and some performance degradation in weightlessness is to be expected in the foreseeable future. Physiological reactions to extended microgravity include a number of hormonal and fluid shifts: the only long-term effect which seems to be both serious and progressively degenerative is a decalcification of bone material. This effect can be retarded to some degree by strenuous exercise, particularly involving compression of the large bones of the leg: this has led to the development of treadmills with elastic cords replacing some of the force of gravity, allowing aerobic running exercises.

Some effort has gone into examining the options for providing appreciable gravity on a space station, by rotating the components to provide a centripetal acceleration. This effect can be quantified as

$$g = w^2 r$$

where  $w$  is the angular velocity, and  $g$  is the effective acceleration at a radius of  $r$ . Early plans (prior to Skylab) indicated that an angular velocity of 4 rpm would be acceptable, producing a required radius of 55.8

m for earth-normal gravity. Some research has suggested that 3 rpm (99.3 m) might be a better rotational velocity for human adaptation, even with a select crew population. If selection standards are relaxed to most of the general population, that implies a rotation speed of 1 rpm, with a resultant radius of 894 m required.

Obviously, it would be extremely complex and expensive to provide stations of this size. One method of easing this requirement would be to provide partial gravity: an early space station proposed with a radius of 25 m at a spin rate of 4 rpm would have produced an apparent gravity of .45 g. However, nothing is known of the effects of partial gravity on bone decalcification or other microgravity effects; this is clearly an important research issue to be addressed by a space station. Short of this information, the logical approach is probably that being considered: do not provide artificial gravity, and rotate the crews at intervals known to be safe, such as three months.

It would be unwise, however, to overly emphasize the limitations of humans, without some equal attention to their assets. The capabilities of humans have been demonstrated repeatedly throughout the history of manned space flight. The list of experiments repaired, satellites retrieved, and missions saved would be too long to go into in this paper. Of greater importance than reviewing the individual performances is to summarize the individual capabilities which made them possible.

Manual dexterity is obviously highly critical for those tasks requiring physical manipulations. No manipulator has yet been developed with anything remotely approaching the dexterity of the human hand. Some experimental efforts in this direction (the Utah/MIT hand and the Salisbury hand) have produced impressive manipulator arm at the current time. The approach taken in the nuclear and the undersea communities (the other two areas for application of general-purpose robotics) have tended towards the use of simple and effectors, and the alteration of tasks to allow for limited dexterity. To some extent, the same is true of space systems designed for EVA involvement: current pressure suit gloves are still far more dexterous than manipulator and effectors, and are likely to continue to evolve in the future.

Strength is (perhaps surprisingly) still an important issue in microgravity. The Remote Manipulator System of the Orbiter is capable of manipulating payloads up to the Orbiter limit of 65,000 lb, but is severely strength-limited, and therefore handling time goes up as mass goes down. The most capable system for retrieval has been shown to be an EVA astronaut in the Manipulator Foot Restraints, attached to an RMS with its joints locked. This configuration was used for grappling the two HS-376 satellites retrieved on shuttle mission STS 51-A, as well as the Leasat HS-393 satellite captured, repaired, and re-released on STS 51-I. This last procedure especially, with the requirement to despin and capture, and later respin and deploy a massive satellite, could not have been effected without the strength and dexterity of a human.

This raises an interesting side point: in most robotic systems available today, manipulators are specialized for either strength or dexterity, but not both. Those arms used for positioning large masses generally do not have the positioning accuracy of arms used for exact pointing or positioning tasks with lightweight payloads. To some extent, the microgravity environment of space may tend to help this problem, as no appreciable strength of the arm will go to maintaining its position in the absence of external forces. At the same time, mass limitations tend to produce lightweight space manipulator designs, requiring either tasks adapted to their flexibility, or sophisticated compensatory control systems to actively reduce the structural modes.

In general, humans are excellent adaptive control systems. Humans routinely change gains and algorithms based on the physical parameters of the system being controlled, and are capable of adapting and changing to a continuously varying system, within limits. Humans improve with practice, and can transfer learned responses to new control tasks of a similar nature.

Humans are especially suited for rapid processing and integration of visual data. From the first manned orbital flights, crews have reported being able to see features on the ground indistinguishable from the best photographic records. Nuances of color, shading, and pattern may be instantly apparent to a human, yet be below the resolution of an electronic imaging system. Humans have the capability to receive and derive spacial information from both static and dynamic scenes, and continuously update their world model based on visual data.

The human capacity for judgement is certainly well-discussed, but it might be maintained that there is a greater utility for low-level reasoning than for intellectual decision-making capability. For example, neutral buoyancy tests of EVA show a human capacity for instinctive maneuvering in the simulated weightless environment, resulting in improvement in task performance without the need for restraints, and without conscious consideration of body actions. This sort of maneuvering, which is computationally complex for a robot, can be performed by a human in "background" mode while concentrating on task planning. While expert system shells will be important for error diagnosis and strategic planning, it is the robotic equivalent of reflexes, instincts, and common sense which will provide the greatest challenge for the artificial intelligence community.

#### FUTURE RESEARCH NEEDS

#### Quantitization

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Many of the important decisions on the applications of humans and machines in space have been (and are currently being) based on prejudices from limited prior experience, a priori arguments, and large, costly system analyses which have no meaningful underlying data base. Certainly, the path of following past experience will probably result in an operable space station. However, much could and should be done to formulate and follow a logical plan for ground-based analyses and simulations, and flight experiments, which would produce a meaningful data base on human

and machine capabilities and limitations in each of the operational categories needed for a successful space station program. There are two caveats for such a program: first, of course, the research must be performed. But equally important, the program managers must be willing to listen and act on the outcomes of the research, and not revert to "tried and true" solutions for the sake of engineering conservatism.

#### Appropriate Roles

One of the outgrowths of the data base development described above would be a greater quantitative understanding of the appropriate roles of humans and machines in space operations, and the most favorable combinations of each to accomplish any particular task. This may imply the altering of traditional roles. For example, as discussed earlier, the flight crew has insisted on maintaining an active, controlling role in those areas critical to safety of flight, or of mission success. However, the (appropriate) risk adversity of mission planners prohibits intuitive solutions to any problem which can be foreseen prior to flight. This has led to the plethora of checklists which describe the appropriate actions of both the flight crew and the ground controllers in any contingency. But, it might be argued, this algorithmic approach obviates the need for most of those capabilities currently unique to humans, such as insight and judgement. Shouldn't this argue for automated systems to implement corrective action in the event of critical malfunctions?

In response to this question, an interesting parallel may be drawn from current findings in aeronautical human factors. With the increased autonomy of transport flight control systems, the airline flight crew are assuming to greater extents than ever the role of system managers. Flight control systems have become capable of completely controlling the aircraft from liftoff through touchdown and rollout. However, serious accidents have already occurred in airline service, due to a flight crew which is neither fully aware of the intricacies of the flight control system, nor highly practiced in manual control of the aircraft. It seems clear that, short of removing the flight deck crew and automating airliners, too much automation breeds overconfidence and inattentiveness in the cockpit; the same will probably be found in space flight.

The conclusion of this argument is to show that it is not enough to fully understand the limitations and capabilities of each of the component technologies: the interactions of the pieces may be far more important to safety and mission success than the pieces themselves. Since the possible number of interactions is a combinatorial problem, it is hopeless to postulate a rigorous or analytical solution to this problem. It is clear, however, that it must be approached in a logical and methodical way if programs as complex as space station are to be successful.

#### Improved Metrics

A problem which is at once conceptually simple and, in implementation, difficult is that of appropriate metrics for human and machine performance in space. Performance indices based on task performance tend to be

unique, or specialized to a small subset of tasks. Indices based on more generic factors, such as motions or subtasks, must take into account the fact that humans and machines may be able to perform the same tasks, but will likely use different techniques in accomplishing them. Even among limited communities, such as EVA, there has yet to form any consensus on the appropriate measurements to produce meaningful comparisons between tasks or experiments. This will be true in larger measure as the field expands to include a wider range of human and robotic activities.

#### An Assessment of Anthropocentrism

Almost all of the designs currently proposed for telerobotic systems are highly anthropocentric: that is, they tend towards a robotic duplication of the human form. Artist's concepts show a head (sensor platform), with two arms mounted on a torso, and with one or two "legs" used for grappling. This approach is understandable for a system which is designed to incorporate (or at least allow) teleoperation, but its assumption for a fully robotic system can only be attributed to engineering conservatism ("stick with a known configuration"). Some recent results from simulation indicate that a number of manipulators with limited degrees of freedom, designed to perform limited or dedicated tasks, may offer performance increased over two anthropomorphic general-purpose manipulators. The human form, evolved in a gravity field for effective protection from predators, is not necessarily the best adaptation for space activities, and alternate forms and technologies should be encouraged and studied carefully.

## CONCLUSION

### THE (FAR?) FUTURE

Given sufficient time, support, and determination, human beings have demonstrated that they are capable of doing almost any physical or intellectual task. They have shown over the last quarter-century that they are fully capable of living and working in space, performing a wide variety of tasks, from the routine and mundane to innovative, immediate actions needed to save a mission or a life. One may postulate a new unit of measurement: the "human-equivalent", or a system in space with the same effectiveness as a single human. Such a system might be composed of a full-time human, living and working in space; of a human in space working part-time with a robotic system; of a teleoperated system controlled by a human on the ground; or even of a fully autonomous robot with learning and reasoning capabilities.

It is clear that the "human-equivalent" presence in space is on a monotonically-increasing curve. As the societies on earth start to gain advantages from space, the need for capabilities in space will continue to grow. This implies a parallel growth in the requirement to operate routinely in space.

As a thought experiment, let us pick that point in the future at which machine systems have become as capable as a human. It may even be maintained that this point is not in the far distant future: manipulative capabilities are already approaching that of a human in a pressure suit, and human decisions on-orbit have been constricted to algorithmic logic

trees easily implemented on modern computers. It is clear that, at some point in time, machines will be capable of performing everything currently done by humans in space. At that point, will we (as a nation, or a civilization) pull all the people out of space, and rely totally on robotic systems to continue the exploration and exploitation of this last, infinite frontier?

At this philosophical question, the author has reached the limits of his original charter. History indicates that humans are capable of performing important, complex tasks in the space environment. As adaptive mechanisms, humans have only begun to learn how to operate in this new environment.

However, much of manned space flight to date has been involved with overcoming the limitations of biological organisms. The evolution of robotic systems has been orders of magnitude more rapid than that of biological systems; there is no reason to assume that this new evolution will stop short of full human capacities, particularly if measured against the currently limited capabilities of humans in space. It is clear that both systems have strengths and weaknesses; that the best mixture of each is a time-dependent solution; and that, for the foreseeable future, the presence of each in space is an absolute necessity for the effective use of the other. If continued development of robotic systems renders humans in space obsolete, that must be a rational, conscious decision made by society as a whole, based on factors beyond those appropriate to an engineering overview paper.

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SHARING COGNITIVE TASKS  
BETWEEN PEOPLE AND COMPUTERS IN SPACE SYSTEMS

William H. Starbuck

New York University

New York, New York

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WHAT ARE THE RELATIVE ADVANTAGES OF PEOPLE AND COMPUTERS?

Mankind's capabilities change very slowly, whereas computers' capabilities have been fast-changing. The cost of a memory component has dropped forty percent per annum for over thirty years, and memory sizes have grown even more rapidly than that (Albus, 1981; Toong and Gupta, 1982). Computation speeds have been accelerating nearly 25 percent yearly, the cost of logic hardware has been dropping equally rapidly, and the computation work done with each unit of energy has been rising thirty percent per annum. Computing hardware has become much more reliable and very much smaller. User interfaces and programming languages have improved considerably, especially over the last decade. If human beings had evolved as rapidly as computers since the mid 1950s, the best runners would now finish a 26-mile marathon in 2.3 seconds, a bright student would complete all schooling from kindergarten through a Ph.D. in a bit over two days, normal eaters would consume one calorie per month, and half of America's families would be earning more than \$141,000,000 annually.

The improvements in computing costs, sizes, and speeds have generally exceeded the most optimistic forecasts of yesteryear, as has the proliferation of computers. Unfulfilled, however, have been the forecasts predicting that computers would shortly be able to imitate human beings. For example, in 1960 Simon optimistically speculated that "Duplicating the problem-solving and information-handling capabilities of the brain is not far off; it would be surprising if it were not accomplished within the next decade" (Simon, 1960:32).

Computers have not, in fact, developed an ability to reason very much like people, and computer simulation of human thought has had little success (Albus, 1981). When computers look most effective solving problems, the computers use quite different techniques than people apply (Weizenbaum, 1965; Winograd and Flores, 1986). For example, Newell et al. (1957) studied students' efforts to prove theorems in mathematical logic, and inferred that the students search for proofs, using heuristics that generally lead toward proofs but do not guarantee them. Challenged by such work, Wang (1963) devised a computer program that efficiently proved all 200 theorems in the first five chapters of Principia Mathematica. Job-shop scheduling affords another example: Scientific-management studies of human production schedulers led to the development of Gantt charts to portray graphically the activities of various machines, and thus to help human schedulers visualize the cascading implications of alternative assignments. Computers generate job-shop schedules by solving integer-programming problems that no human could solve correctly without machine assistance.

The differences between people and computers have an illusory quality, insofar as people tend to take prevalent human abilities for granted and to notice rare or inhuman abilities. If computers did operate exactly like people do -- working at the same speeds, making the same mistakes, showing the same fatigue, complaining about unpleasant tasks, and so on -- people would regard computers merely as inhuman labor. Computers most impress people when they augment human abilities significantly -- by working silently and tirelessly, by calculating with dazzling speed, or by displaying total consistency.

But the quite real differences between people and computers are persistent and profound. Rather than regard computers as potential imitators of human beings, it makes better sense to look upon them as a distinct species -- a species that prefers different languages, reasons with somewhat different logic, finds comfort in different habitats, and consumes different foods.

Computers are much better symbol manipulators and much stricter logicians than people; and computers are much more decisive, literal, precise, obedient, reliable, consistent, and transparent. Computers can act both much more quickly and much more slowly than people. If so instructed, computers will carry out utterly absurd instructions or they will remain completely calm in the face of impending disaster. Computers easily simulate what-if conditions; and they can extrapolate even the most farfetched implications of theories or conjectures.

People, on the other hand, possess brains that are so much more complex than the largest computers that comparisons make no sense. These brains carry on numerous simultaneous and interacting processes, some of which operate entirely automatically. Without even trying, people process visual and auditory data of great complexity. People can shift levels of abstraction from detail to generality and back, they separate foreground images from background images, they distinguish patterns while remaining aware of contexts, and they attend to important or unusual stimuli while ignoring unimportant or routine stimuli. People have quite extensive memories that possess meaningful structures; and if they have relevant

information in their memories, people usually know it and they can usually find it. People can operate with imprecise and somewhat incomplete plans, and they can extrapolate their past experiences to novel situations while recognizing that they are indeed operating outside the limits of their direct experience (Allen, 1982; Dreyfus and Dreyfus, 1986; Moray, 1986; Reason, 1986; Winograd and Flores, 1986).

Perhaps most importantly, people are more playful than computers and better at making mistakes. Whereas computers obey instructions literally, people often ignore or forget instructions, or interpret them loosely. Not only do people tend to deviate from plans and to test the limits of assumptions, but many human perceptual skills and response modes depend on observing deviations from expectations or goals that may be evolving. Sometimes, people begin to doubt even their most basic beliefs. Thus, people generally expect to make mistakes and to learn from them, and creative people may be very good at learning from mistakes. If they have sufficient time, people can learn to correct their mistakes and they can reprogram themselves to take advantage of unexpected situations. Although computers also observe and react to deviations, computers have not yet exhibited much capability to devise goals for themselves, to reprogram themselves, or to question their own basic premises (Valiant, 1984). Computers must be told to learn from their experiences, and efforts to enable them to learn have, so far, been restricted to very narrow domains of activity. Also, computers are good at not making mistakes in the first place, so they have less need to learn from mistakes.

People are, however, pretty diverse and flexible. Some people can learn skills and perform tasks that other people find impossible; and since NASA can choose from a large pool of applicants, the extreme capabilities of exceptional people are more important in space systems than the average capabilities of typical people. The people who operate space systems first receive thorough training, so their deficits of inexperience should be small; but this training itself may impose serious liabilities, such as a tendency to rely on well-practiced habits in novel situations.

Because people are flexible and complex, they often surprise scientists and systems designers: People may change their behaviors significantly in response to ostensibly small environmental changes, or people may change their behaviors hardly at all in response to apparently large environmental changes. How people react to a situation may depend quite strongly on the sequence of events leading up to that situation, including the degree to which the people see themselves as having helped to create the situation. Accurate statements about microscopic details of human behavior rarely prove accurate as statements about general, macroscopic behavioral patterns, or vice versa. For example, experimental studies of people who are being paid low hourly wages for making repeated choices between two clearly defined, abstract symbols that have no implications for later events probably say little about human behavior in real-life settings where actions may have persistent and personally significant consequences and where actors may not even perceive themselves as having choices. Conversely, broad generalizations about the behaviors of most people in diverse situations probably say little about the

behaviors of carefully selected people who are performing unusual tasks in which they have great experience.

The research issues that are important for designing human-computer systems seem to be ones concerning the proper balances among opposing advantages and disadvantages, rather than ones demanding new concepts; and the best resolutions of these issues are certain to shift as computers acquire greater capabilities. Consequently, I will not attempt to state any generalizations about the proper dividing lines between human and computer responsibilities in space systems, and I am not advocating any research aimed at describing human capabilities in general. The designers of space systems should not depend on general theories, but should test fairly realistic mock-ups of interfaces, hardware, and software, with people who are as well trained and as able as real astronauts and controllers. The designers should also investigate the sensitivity of performance measures to small variations in their designs (Gruenenfelder and Whitten, 1985): Do small design changes produce large changes in performance? Both to improve the quality of designs and to improve users' acceptance of designs, experienced astronauts and controllers should participate in the designing of interfaces and systems; and because early decisions often constrain later modifications, astronauts and controllers should participate from the beginning of any new project (Grudin, 1986).

#### PEOPLE INTERACTING WITH COMPUTERS

Today's computers cannot imitate people very closely, but the differences between people and computers imply that combinations of the

two can achieve results beyond the capabilities of each alone. For that reason, NASA should devote research effort to improving the interactions and synergies between people and computers.

Five research topics seem especially interesting and important because (a) I can see how to pursue them and (b) I can foresee some research findings that would translate directly into improved performances by space systems.

1. Fostering Trust Between People and Expert Systems
2. Creating Useful Workloads
3. Anticipating Human Errors
4. Developing Effective Interface Languages
5. Using Meaningful Interface Metaphors

#### Fostering Trust Between People and Expert Systems

Decision-support systems are computer programs and data bases that are intended to help people solve problems. Some decision-support systems merely afford their users easy access to data; other decision-support systems actually propose solutions, possibly basing these proposals on data supplied by their users (Woods, 1986b).

Expert systems are decision-support systems that attempt to embody the specialized knowledge of human experts. Their proponents argue that expert systems can, in principle, make specialists' knowledge available to nonspecialists: every CPA might be able to draw upon the combined expertise of several tax specialists; every general practitioner might be

able to make subtle diagnoses that reflect advanced training in many specialties. Expert systems might perform even better than human experts: Computers may be able to obtain data that would be unavailable to people (Burke and Normand, 1987). Computers' huge memories and high speeds might enable them to investigate more alternatives or to take account of more contingencies than people consider. Computers may also avoid some of the logical errors to which people typically fall prey, and thus may draw some inferences that people would miss (Bobrow et al., 1986). Advocates of statistical decision theory value computers' ability to adhere quite strictly to such formulae. Some proposals would have computers formulating recommendations and people then screening these recommendations and deciding whether to accept them (Burke and Normand, 1987; Dreyfus and Dreyfus, 1986; Woods, 1986a, 1986b).

Not everyone holds an optimistic view of expert systems' potential. Stanfill and Waltz (1986:1216) remarked: "Rule-based expert systems ... tend to fail badly for problems even slightly outside their area of expertise and in unforeseen situations." Dreyfus and Dreyfus (1986:108) have argued that human experts do not follow decision rules but instead they remember "the actual outcomes of tens of thousands of situations", and that "If one asks the experts for rules one will, in effect, force the expert to regress to the level of a beginner and state the rules he still remembers but no longer uses." Consequently, Dreyfus and Dreyfus (1986:109) predicted "that in any domain in which people exhibit holistic understanding, no systems based upon heuristics will consistently do as well as experienced experts, even if those experts were the informants who provided the heuristic rules."

Dreyfus and Dreyfus' critique may be valid. Dutton and I (1971) spent six years studying an expert production scheduler named Charlie, including one full year investigating his procedure for estimating how much production time any schedule represented. Charlie estimated time by using the relation:

$$\text{Production Time} = \text{Schedule Length} / \text{Speed}$$

"We gradually were disabused of the idea that Charlie has a computation procedure for speed and were convinced that he obtains his speed estimates by a table look-up. That is, Charlie has memorized the associations between speed and schedule characteristics, and he looks up speeds in his memory in somewhat the way one looks up telephone numbers in a directory. In our interviews, Charlie talked as if the existence of a computation procedure was a novel idea, intriguing to contemplate but difficult to conceive of. He thinks of the speeds in his table as discrete numbers distilled from a long series of unique experiences. Although he can interpolate and extrapolate these numbers -- implying that the stored speeds must be specific examples from a systematic family of numbers -- he distrusts the interpolated values and speaks of them as hypotheses to be tested in application. The stored values are so much more reliable that they might be a different kind of information altogether. In fact, Charlie can recount, for a large proportion of his table entries, specific remembered situations in which the circumstance was encountered and the speed observed. The only speeds that he does not so document, apparently, are those appropriate to situations arising almost daily" (Dutton and Starbuck, 1971:230).

We calculated that Charlie had memorized approximately 5000 production speeds corresponding to various situations. But we also discovered that Charlie's production-time estimates could be predicted quite accurately by a simple linear equation that had a meaningful and generalizable interpretation in terms of the physics of the production process. Rather than thousands of machine speeds, this linear equation required only a few hundred parameters. Thus, we could state a procedure that was simpler than the one Charlie used; and because this artificial procedure had a physical interpretation, a user could more confidently extrapolate it to novel production situations.

One of the best-known expert-system projects not only produced a heuristic program, DENDRAL, but also led to the development of an efficient algorithm for generating molecular structures (Bennett et al., 1981). Evidently, the heuristic program has received little practical use whereas the algorithm has had much (Dreyfus and Dreyfus, 1986).

One obvious question is: why must expert systems closely resemble human experts? The proponents of expert systems typically equate expertise with human beings, so they see imitating human expertise as essential to creating expert systems; and their critics focus on the differences between computers and people. Yet, computers possess different abilities than people. Computer programming efforts that have begun by imitating human behavior have often ended up using techniques that made no pretense of imitating human behaviors; and engineers and

scientists have devised, without imitating human expertise, many techniques that enable computers to exceed the best of human capabilities.

Other questions arise concerning people's willingness to depend upon computer-based expertise. Collins (1986) interviewed actual and potential users of several widely known expert systems for accounting, chemical analysis, mathematics, medical diagnosis, and computer-components ordering. She found only one of these expert systems that has active users: the one for ordering computer components (R1). It has straight-forward logical processes and it draws no subtle inferences; it mainly helps sales personnel forget no details when they fill in orders, and the sales personnel said they appreciated not having to waste their time worrying about details or waiting for access to a human expert. It may be relevant that the users of this system sold computing equipment. Concerning the other expert systems, potential users expressed considerable distrust, of other human experts as well as computers; and the potential users may view these systems as threatening their own expertise. However, the people who actually participated in creating these systems said they do trust them and would, but do not, use them. Collins inferred that trust in an expert system comes either from participating in the design process or from being able to change the system to reflect one's own expertise. This inference meshes with the general pattern of psychological research, but neither of these options was available to the computing-equipment sales personnel, who were the users voicing the greatest trust in an expert system.

Complex issues surround the idea that a user should screen an expert system's recommendations and decide whether to accept them. If an expert system draws the same inferences that its user would draw and if it recommends the same actions that the user would choose, that user will easily learn to trust the system. Such seems to be the case with the expert system for computer-components ordering. Such a system may relieve people from having to perform boring or easy work, but it adds very little to a user's intellectual capabilities, whereas in principle, computers' precise logic and extensive computation capabilities and the incorporation of exceptionally high-quality expertise might enable expert systems to draw substantially better inferences than their users and to choose distinctly better actions. Yet a user is quite likely to distrust an expert system that draws significantly different inferences and that chooses significantly different actions than the user would do. If the expert system also uses a computational procedure that diverges quite dramatically from human reasoning, the system may be unable to explain, in a way that satisfies users, why it draws certain conclusions and not others. Distrustful users may never discover whether an expert system is making good recommendations or bad ones.

This calls to mind the experience of a manufacturing firm that installed one of the first computer-based systems for job-shop scheduling. The system's creators promised that computer-generated schedules would produce considerable savings in comparison to human-generated schedules. The factory's managers, however, were not entirely sure of the goodness of computer-generated schedules, and they wanted to minimize the implied insult to their human production

schedulers, so the managers told the schedulers to follow the computer's recommendations as long as they agreed with them, but to substitute their own judgement when they thought the computer had made bad recommendations. An evaluation conducted after one year showed that the computer-based system had yielded no improvements whatever.

But research may be able to suggest some answers to these issues, at least in part; and good design may be able to resolve them: Expert systems, even the ones that cannot meaningfully explain the reasoning that leads them to make certain recommendations, should be able to explain why they believe their recommendations to be good. People who cannot formulate a good recommendation may be able to recognize a good recommendation or a bad one, and people do sometimes recognize their own limitations. At least some of the people who manage factories have learned to trust computer programs for production scheduling or inventory control even though these people could not themselves generate the computers' solutions.

The foregoing observations highlight the practical significance of research about the factors that influence people's trust in computers' expertise. In what ways should a decision-support system's knowledge and logical rules fit each user individually? Given opportunities to tailor interfaces to their personal preferences, inexperienced users may design interfaces poorly (Dumais and Landauer, 1982): Do users trust systems more or less when tailoring is postponed until the users gain considerable experience? How do task characteristics affect a user's willingness to trust a decision-support system? In what circumstances does a user decide

to trust a computer system that captures the knowledge of experts whom the user does not know personally? What kinds of experiences lead a user to trust a decision-support system that the user regards, at least partly, as a blackbox? What kinds of experiences encourage a user to see a decision-support system's limitations and to override bad recommendations?

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#### Creating Useful Workloads

Automation tends to make computers responsible for routine, easy tasks and to leave the nonroutine, difficult tasks for people. One reason for this may be the perception that nonroutine tasks are interesting and challenging, and thus worthy of human attention, whereas routine tasks appear easy and uninteresting, and so demeaning to people. But a more important reason may be the practicality that designers can figure out how to automate routinized activities whereas they cannot effectively automate activities that vary.

This division of labor produces the consequence that, as automation progresses, people's work becomes more and more diverse and unpredictable and it takes on more and more of an emergency fire-fighting character. At the same time, cutting people out of routine tasks isolates them from on-going information about what is happening and forces them to acquire this information while they are trying to perform nonroutine, difficult tasks. The human controllers in a system may not even be warned of gradually developing problems until the system exceeds critical limits and alarms go off (Weiner, 1985). Thus, people's work grows less do-able and

more stressful (Senders, 1980); and extreme stress and extreme time pressure may cause people to do poorer work and less of it.

In many tasks, automation also increases the short-term stability of the variables used to monitor performance; as Weiner (1985:83) put it, "automation tunes out small errors and creates opportunities for large ones." De Keyser (1986) has suggested that this short-term stabilization causes the human operators to shift from an anticipation logic to a recovery logic: instead of keeping track of events and trying to manage them, the operators wait for significant undesirable events to occur. Furthermore, "At the highest automation stage, the production operator has only very sketchy operating images of process and installation.... He will not make a huge investment in observation, checking, judging, establishing relationships, gathering of data without being certain of its usefulness. The operator does not invest psychologically in a role which escapes him" (De Keyser, 1986:234-235). Hence, De Keyser et al., (1986:135) have advocated that "the person still play an active part in the ongoing activity, not because this presence is required, but because it automatically keeps the person up to date on the current status of the system, the better to respond if an emergency situation develops." This seems a plausible hypothesis, but an equally plausible hypothesis would be that operators tend to work mechanistically when they are performing the kinds of activities that could be automated.

De Keyser also, however, pointed out that serious emergencies call for as much automation as possible because they produce extreme time pressures, extremely complex problems, and extreme dangers -- all of which

greatly degrade the capabilities of human operators. Of course, people are utterly unable to respond as quickly as some emergencies demand. This poses a Catch-22. As long as the designers of a system have sufficient understanding to be able to prescribe how the system should respond to a serious emergency, they should incorporate this understanding in the system's automatic responses. But such complete understanding should imply that the automatic system works so well that a planned-for serious emergency never occurs. Consequently, when a serious emergency does arise, is not design error one prominent hypothesis about its cause, and does that hypothesis not render suspect the diagnostic information being produced by the system? Any system-design process establishes a frame of reference that identifies some events as relevant and important, and other events as irrelevant or unimportant; and a cost-effective system monitors the relevant and important events and ignores the irrelevant and unimportant ones. But this is likely to mean that the system lacks information about some of the events that produce a serious emergency, and the incomplete information that the system does have available may well lead human diagnosticians astray. Moreover, human operators who participate continuously in a system might grow so familiar with the system and its current status that they overlook anomalies and lack the objectivity to respond effectively to a serious emergency.

Trying to diagnose the causes of an unexpected emergency and to develop remedies, human operators must understand computers and other machines extremely well, which implies that they are quite comfortable with computers and with the causal models they incorporate; but on the other hand, human operators must distrust their computers and

computer-based models sufficiently to be able to sift computer-generated information with skeptical eyes. Similarly, confidence in their training can help people remain calm in an emergency, but confidence in their training also blinds people to its shortcomings. It thus seems likely that the people who do the most good in emergencies have an ability to discard their preconceptions and to look at situations from new points of view (Luchins and Luchins, 1959; Watzlawick et al., 1974). NASA should investigate the degrees to which such an ability varies among people and can be predicted or taught.

Workloads vary in duration as well as intensity. People can cope with very intense workloads for short periods, yet they experience stress from moderate workloads that persist for long periods (Turner and Karasek, 1984). Some physiological reactions to stress, such as ulcers and vulnerability to infection, take time to develop. Thus, the short-duration shuttle flights do not afford a good basis for forecasting the workloads to be experienced on long-duration tours in a space station. NASA should continue to investigate the workload experiences gained from long stays in confined spaces such as Antarctica, Sealab, and nuclear submarines (Bluth, 1984).

#### Anticipating Human Errors

Overloading causes people to make errors, but so do boredom, inattention, and indifference. Human errors are both prevalent and inevitable (Senders, 1980), and many human errors are desirable despite their costs. People experiment, and some of their experiments turn out

badly. People deviate from their instructions, and some of these deviations have bad consequences.

Norman (1983, 1986) and Reason (1979, 1986) have initiated research into the causes of errors and ways to prevent or correct them. Norman, for instance, distinguished errors in intention, which he called mistakes, from errors in carrying out intentions, which he called slips. He classified slips according to their sources, and then sought to prescribe remedies for various slips. Table 1 lists some of Norman's categories and prescriptions.

Recognizing errors' importance, NASA's Human Factors Research Division is currently conducting some well-thought-out research on error-detection and on error-tolerant systems. Error-detection systems would warn people when they appear to have omitted actions, to have acted out-of-order, or to have taken harmful actions. Error-tolerant systems would first detect human errors through unobtrusive monitoring and then try to remedy them.

This research has much to recommend it. But some errors are very costly to tolerate, and some errors are very costly or impossible to correct. So human-computer systems should also try to predict human errors in order to make serious errors unlikely in advance (Schneider et al., 1980; Shneiderman, 1986). That is, prevention may be cheaper and more effective than cure, and research on error prevention might usefully complement the current projects.

Of course, all human-computer systems express some assumptions about their human participants. These assumptions have nearly always been implicit; and they have nearly always been static, insofar as the assumptions have not changed in response to people's actual behaviors (Rouse, 1981; Turner and Karasek, 1984). For many tasks, it would be feasible to explicate fairly accurate models of people. In fact, models need not be very accurate in order to make useful predictions or to suggest where adaptability to people's actual behaviors might pay off. Computers might, for example, predict that people who respond to stimuli quickly are more alert than people who respond slowly; or they might predict that experienced people would respond more quickly than inexperienced ones; or they might predict that people would be more likely to behave in habitual ways than in unusual ways; or they might predict that people would be less concerned about small discrepancies when much activity is occurring. Based on a review of human-factors research, Simes and Sirsky (1985) hypothesized that:

- o experience or frequent use of a computer system decreases people's need for immediate feedback (closure),
- o experience or frequent use decreases the importance of human limitations in information processing,
- o experience or frequent use decreases the impact of sensory overstimulation,
- o task complexity increases inexperienced people's need for immediate feedback,

- o task complexity increases the importance of human limitations in the information processing by inexperienced people, and
- o task complexity increases the impact of sensory overstimulation.

As NASA's human-factors scientists well understand, computers that predict, detect, and remedy human errors raise issues about who is actually in control. When should people have the right to experiment or to deviate from their instructions?

### Developing Effective Interface Languages

Communication between people and computers may resemble communication between people who come from very different backgrounds, say a tribesman from the Kalahari desert and a whiz-kid mathematician from Brooklyn. Because computers do differ from people, the people who interact with computers need to remain aware of these differences, and the interfaces for human-computer interaction should remind users of these differences. This need became clear during the 1960s, when Weizenbaum created a program, ELIZA, that conversed in English. ELIZA had almost no understanding of the topics about which it conversed. Instead, it imitated blindly the vocabularies of the people with whom it conversed; in effect, ELIZA merely repeated people's words back to them. Yet Weizenbaum (1976:6) observed: "I was startled to see how quickly and how very deeply people conversing with [ELIZA] became emotionally involved with the computer and how unequivocally they anthropomorphized it."

Weizenbaum's more colorful examples concerned people who did not have close acquaintance with computers. Nearly all of the research on human-computer interaction has focused on people who lacked thorough training and who had little experience with computers. Although such research findings can benefit the design of training programs, design characteristics that have strong effects on novices may have negligible effects on expert users, so most of these findings may not extrapolate to the well-trained and experienced operators of space systems. There is need for studies of well-trained and experienced users.

Sheppard, Bailey, and their colleagues (Sheppard et al., 1980, 1984) have run experiments with professional programmers having several years of experience. The first three experiments involved programs or program specifications that were stated either in flowchart symbols, or in a constrained program-design language, or in carefully phrased, normal English. These experiments asked experienced programmers to answer questions about program specifications, to write and debug programs, or to correct faulty programs. The fourth experiment omitted flowchart symbols and substituted an abbreviated English in which variables' names replaced their English descriptions; and the programmers were asked to add instructions to programs. Table 2 summarizes the results: Normal English turned out to be consistently inferior, and the program-design language proved consistently superior.

One liability of a natural language such as English is its generality: Because vocabularies are large and linguistic structures are flexible, much ambiguity surrounds each word, phrase, and sentence.

Speakers can make statements that mean almost anything, or nothing. Even a restricted natural language, probably because it resembles unrestricted natural language, may make users uncertain what commands are legitimate and meaningful to the computer system (Jarke et al., 1985; Shneiderman, 1986). Ambiguity and unused complexity create noise.

Both people and computers absorb information faster and more accurately when their interactions make good use of themes, chunking, and sequences (Badre, 1982; Simes and Sirsky, 1985). Overall themes can help people or computers to predict what information to expect and what information is important. Effective chunking aggregates information into batches that have meaning within the context of specific tasks. Effective sequencing presents information in a familiar, predictable order. Themes, chunking, and sequences can improve communication in any language, but they may become more important when a language has more generality.

A second liability is that natural language evokes the habits of thinking and problem solving that people use in everyday life. Green et al. (1980:900-901) remarked, for example:

"The fundamental strategies of parsing used by people seem, in fact, to be aimed first and foremost at avoiding parsing altogether

- (i) if the end of the sentence can be guessed, stop listening;
- (ii) if semantic cues or perceptual cues (boldface, indenting, pitch and stress in speech) are enough to show what the sentence means, stop parsing;

- (iii) if syntactic signals (and, -s, -ly, etc.) are available, use them to make a guess at the sentence structure;
- (iv) if there is no help for it, make a first shot at parsing by cementing together the closest acceptable pairings -- noun to the nearest verb, if to the next then, etc.;
- (v) only if that first shot fails, try to figure out the structure by matching up constituents properly.

Not until Step (v) does the human start to parse in a manner anything like the computer scientists' idea of parsing; and the phrase 'figure out' has been used advisedly, for by the time that step is reached people are doing something more like problem solving than routine reading or listening."

Information displays can improve comprehension by offering symbolic and, especially, perceptual cues that help people to interpret messages. However, designing good displays is made complicated by the potentially large effects of overtly small cues. In a study of a command language, for instance, Payne et al. (1984) found that users' errors dropped 77 percent when the operator words were displayed in upper case and the operands were displayed in lower case, thus providing visual distinction between the two categories. Further, changes that improve performance in one context often degrade performance in another context, and changes that improve one dimension of performance often degrade another dimension of performance. A flowchart, for example, may help users to trace forward to the consequences of some initial conditions but it may impede their backward inferences about the antecedents of some terminal conditions (Green, 1982).

A third liability may be that natural languages lead users to assume that computers' reasoning resembles human reasoning, whereas artificial programming or query languages remind users that computers' reasoning differs from human reasoning. This suggests that languages resembling natural ones might be more effective media for communication between people and computers in contexts where the computers closely simulate human reasoning and understanding, even though artificial languages might be more effective communication media in applications where computers deviate from human reasoning.

Unstudied so far are the interactions between social contexts and interface languages; virtually all studies of interface languages have involved people working on tasks that they could perform alone. Yet space systems create strong social contexts. The operators talk with each other while they are interacting with computers: Queries between people instigate queries to computers, and messages from computers become oral statements to other people. De Bachtin (1985) found that sales personnel who were interacting with a computer and customers simultaneously greatly preferred an interface that allowed them to pose queries in rather free sequence and phrasing. Thus, interface languages that approximate natural languages might turn out to be more valuable in space systems than in the situations that have been studied.

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Using Meaningful Interface Metaphors

One very significant contribution to human-computer interaction was Xerox's Star interface, which derived from many years of research by many researchers. The Star interface embodies a number of design principles that evolved from experiments with prototypes. According to Canfield Smith et al. (1982:248-252), "Some types of concepts are inherently difficult for people to grasp. Without being too formal about it, our experience before and during the Star design led us to the following classification:

<u>Easy</u>	<u>Hard</u>
concrete	abstract
visible	invisible
copying	creating
choosing	filling in
recognizing	generating
editing	programming
interactive	batch

The characteristics on the left were incorporated into the Star user's conceptual model. The characteristics on the right we attempted to avoid....

"The following main goals were pursued in designing the Star user interface:

- familiar user's conceptual model
- seeing and pointing versus remembering and typing
- what you see is what you get
- universal commands
- consistency
- simplicity
- modeless interaction
- user tailorability

"...We decided to create electronic counterparts to the physical objects in an office: paper, folders, file cabinets, mail boxes, and so on -- an electronic metaphor for the office. We hoped this would make the electronic 'world' seem more familiar, less alien, and require less training.... We further decided to make the electronic analogues be concrete objects. Documents would be more than file names on a disk; they would be represented by pictures on the display screen. They would be selected by pointing to them.... To file a document, you would move it to a picture of a file drawer, just as you take a physical piece of paper to a physical file cabinet."

NASA's Virtual Environment Workstation illustrates a much more avant-garde metaphor (Fisher et al., 1986). This project would give a robot's operator the sensations and perspective of the robot: Screens in the operator's helmet would show views taken by cameras on the robot;

sensors would pick up the operator's arm and finger movements and translate them into movements of the robot's arms; and the operator's gloves would let the operator feel pressures that the robot's fingers feel. The operator would have the sensation of being inside the robot, and the robot would become an extension of the operator's arm and hand movements, even though the robot might be many miles from the operator.

Although metaphors constitute a fairly new frame of reference for the designers of interfaces, a designer or user can look upon every interface as a metaphor of something, and thus the design issue is not whether to adopt a metaphor but what metaphor to adopt. Each metaphor has both advantages and disadvantages. As Star's designers noted, an effective metaphor can both reduce the amount of learning that inexperienced users must do and accelerate that learning. An effective metaphor can also tap into users' well-developed habits and thereby reduce errors and speed responses; and experienced users as well as inexperienced users show such improvements. For instance, Ledgard et al. (1980) slightly modified a text editor so that its commands resembled short English sentences: The original, notational command `RS:/KO/,/OK/*` became `CHANGE ALL "KO" TO "OK"`, and the notational command `FIND:/TOOTH/` became `FORWARD TO "TOOTH"`. As Table 3 shows, such changes improved the performances of fairly experienced users as well as inexperienced users.

But every interface metaphor breaks down at some point, both because a metaphor differs from the situation it simulates and because an interface differs from the computer it represents. People in real offices can take actions that users cannot simulate in Star's electronic office, and Star's

electronic office allows actions that would be impossible in a real office. Similarly, a robot might be unable to reproduce some of its operator's instinctive finger movements, and an operator in a shuttle or space station would lack the mobility of an unconfined robot. Yet, users are likely to draw strong inferences about a computer's capabilities from the human-computer interface. Ledgard et al. (1980:561) noticed that "the users made no distinction between syntax and semantics.... To them, the actual commands embodied the editor to such an extent that many were surprised when told after the experiment that the two editors were functionally identical."

One implication is that an interface metaphor, like an interface language, should maintain some intentional artificiality in order to warn users of its limitations. Are some of the intuitive expectations that users bring to metaphors especially important to fulfill? For example, in designing the Virtual Environment Workstation, might it be essential to use cameras that closely approximate the spacing and movements of human eyes in order to avoid having to retrain the operator's stereoscopic vision? Under stress, people tend to revert from specific, learned, complex models back to generic, commonsense, simple models: Which of the expectations that users have unlearned through training does stress reawaken? Does stress, for instance, increase users' responsiveness to concrete, visible stimuli and decrease their responsiveness to abstract, invisible stimuli?

A second implication is that designers should carefully explore the limitations of an interface metaphor before they adopt it, and they should

look upon a metaphor as one choice from a set of alternatives, each of which has advantages and disadvantages. However, the existing interface metaphors have been developed separately, with considerable emphasis being given to their uniqueness; and the processes that developed them have been poorly documented. So, interface designers need to be able to generate alternative metaphors, they need conceptual frameworks that highlight the significant properties of different metaphors, and they need systematic research to document these properties.

\* \* \*

All of the foregoing topics imply that a computer should adapt both its appearance and the rules in programs to its user -- to take account, for example, of its user's technical expertise, experience, frequency of use, or manual dexterity. This calls for development of sophisticated interface software (a so-called User Interface Management System) that will recognize the needs of different users, allow different users to express their personal preferences, and protect users' individuality. Thus, the computer needs to be able to identify a user quickly and unequivocally, and if possible, without imposing an identification procedure that would irritate people or delay their access in an emergency.

#### PEOPLE ADD IMAGINATION AND POETRY

Efforts to justify space systems in economic terms will keep pressing for higher and higher levels of measurable productivity, and so planners

will tend to program the operators' activities in detail. But very heavy workloads raise the probabilities of human error, and computers will always be better than people at working tirelessly and obediently adhering to plans. People contribute to space systems their ability to deal with the unexpected, and in fact, to create the unexpected by experimenting and innovating. They can make these contributions better if they are allowed some slack.

Space systems' tasks are not all located in space. Space systems inevitably make educational contributions that transcend any of their immediate operational goals. One of the major contributions of the space program to date has been a photograph -- a photograph of a cloud-bedecked ball of water and dirt isolated in a black void. Before they saw that photograph, people's understanding that mankind shares a common fate had to be abstract and intellectual; the photograph has made this understanding more tangible and visceral.

People play central roles in educational activities because they serve as identifiable points of reference in settings that would otherwise seem mechanistic, remote, and alien. Another of the space program's major contributions, because it put space exploration into words that caught the human imagination, was Neil A. Armstrong's unforgettable observation: "That's one small step for a man, one giant leap for mankind" (July 20, 1969).

**DRAFT**

Fostering Trust Between People and Expert Systems

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In what ways should a decision-support system's knowledge and logical rules fit each user individually? Do users trust systems more or less when tailoring is postponed until the users gain considerable experience?

How do task characteristics affect a user's willingness to trust a decision-support system?

In what circumstances does a user decide to trust a computer system that captures the knowledge of experts whom the user does not know personally?

What kinds of experiences lead a user to trust a decision-support system that the user regards, at least partly, as a black-box?

What kinds of experiences encourage a user to see a decision-support system's limitations and to override bad recommendations?

Creating Useful Workloads

Does performing activities that could be automated actually keep human operators up to date on the status of a system, or do operators tend to work mechanistically when they are performing routine activities? Do

human operators who perform activities that could be automated respond more effectively to a serious emergency because their participation updates them on the current status of the system, or does continuous participation make operators so familiar with the system and its current status that they overlook anomalies and lack the objectivity to respond effectively to a serious emergency?

NASA should investigate the degrees to which an ability to discard preconceptions varies among people and can be predicted or taught.

What have been the workload of experiences during long stays in confined spaces such as Sealab, Antarctica, and nuclear submarines?

#### Anticipating Human Errors

Research on error prevention might usefully complement the current projects on error detection and error tolerance. For many tasks, it would be feasible to explicate fairly accurate models of people that would enable human-computer systems to predict and adapt to human errors. In fact, models need not be very accurate in order to make useful predictions or to suggest where adaptability to people's actual behaviors might pay off.

#### Developing Effective Interface Languages

Virtually all studies of interface languages have involved individual people working on tasks that they could perform alone. Because space

systems create strong social contexts, interface languages that approximate natural languages may turn out to be much more valuable in space systems.

#### Using Meaningful Interface Metaphors

Are some of the intuitive expectations that users bring to metaphors especially important to fulfill?

Under stress, people tend to revert from specific, learned, complex models back to generic, commonsense, simple models: Which of the expectations that users have unlearned through training does stress reawaken?

Interface designers need to be able to generate alternative metaphors, they need conceptual frameworks that highlight the significant properties of different metaphors, and they need systematic research to document these properties.

#### General

NASA should develop a sophisticated User Interface Management System that will recognize the needs of different users, allow different users to express their personal preferences, and protect users' individuality.

Is there a way for a computer to identify its user quickly and unequivocally, without imposing an identification procedure that would irritate people or delay their access in an emergency?

Since NASA can choose from a large pool of applicants, the extreme capabilities of exceptional people are more important than the average capabilities of typical people.

The people who operate space systems first receive thorough training, so their deficits of inexperience should be small. Nearly all of the research on human-computer interaction has focused on people who lacked thorough training and who had little experience with computers, so most of these findings may not extrapolate to the well-trained and experienced operators of space systems. There is need for studies of well-trained and experienced users.

Avoid research aimed at describing human capabilities in general. Instead, test fairly realistic mock-ups of interfaces and systems, with people who are as well trained and as able as real astronauts and controllers.

Investigate the sensitivity of performance measures to small variations in designs: Do small design changes produce large changes in performance?

Both to improve the quality of designs and to improve users' acceptance of designs, experienced astronauts and controllers should participate in the designing of interfaces and systems. Because early decisions often constrain later modifications, astronauts and controllers should participate from the beginning of any new project.

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TABLE 1 Some Error Categories and Prescriptions

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Forming the Wrong Intentions

Mode errors:

misclassifications of systems' modes	Eliminate modes. Give better indications of modes. Use different commands in different modes.
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Description errors:

ambiguous statements of intentions	Arrange controls meaningfully. Give controls distinctive shapes. Make it difficult or impossible to take actions that have serious, irreversible consequences.
------------------------------------	--

Misdiagnoses:

Suggest alternative  
explanations.

Point out discrepancies  
that might be  
overlooked.

Activating the Wrong Behaviors or Triggering Behaviors at the Wrong  
Times

Omissions:

Remind people of  
uncompleted actions.

Capture errors:

very familiar behaviors replace  
less familiar behaviors

Minimize overlapping  
behaviors.

Monitor actual behaviors  
where similar behavior  
sequences diverge.

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SOURCE: Norman (1983, 1986)

TABLE 2 How Experienced Programmers' Performances Vary with  
Different Languages

First experiment: answer questions about program specifications

	Normal English	Flowchart Symbols	Program-design Language
Time needed to answer:			
Forward-tracing questions	45.9	37.6	35.1
Backward-tracing questions	46.8	37.6	35.8
Input-output questions	42.9	39.4	41.0
Percent of programmers preferring	14	33	53

Second experiment: write and debug programs

	Normal English	Flowchart Symbols	Program-design Language
Time needed to write and debug programs	29.7	23.9	20.5
Editor transactions before solution	37	39	32
Attempts before solution	3.0	2.7	2.2
Semantic errors	2.4	1.4	.8
% of programmers preferring	6	35	59

Third experiment: correct faulty programs

	Normal English	Flowchart Symbols	Program-design Language
Time needed to correct faulty programs	18.7	14.2	14.5
Attempts before solution	1.9	2.2	1.9
Percent of programmers preferring	33	34	33

Fourth experiment: modify and debug programs

	Normal English	Abbreviated English	Program-design Language
Time needed to modify and debug	28.1	26.6	25.0
Semantic errors	.9	1.3	1.0
Percent of programmers preferring	18	32	50

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SOURCE: Sheppard et al. (1980, 1984)

TABLE 3 Text Editing With Different Command Languages

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	English-like Commmands	Notational Commands
<u>Users with less than 6 hours of experience:</u>		
Percentage of tasks completed correctly	42	28
Percentage of erroneous commands	11	19

Users with more than 100 hours of experience:

Percentage of tasks completed correctly	84	74
Percentage of erroneous commands	5.6	9.9

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SOURCE: Ledgard et al. (1980)

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THE HUMAN ROLE IN SPACE SYSTEMS

A COMMENTARY ON THE

AKIN AND STARBUCK PAPERS

Harry L. Wolbers, Ph.D.

McDonnell Douglas Astronautics Company  
Huntington Beach, California

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THE HUMAN ROLE IN SPACE SYSTEMS  
A COMMENTARY ON THE AKIN AND STARBUCK PAPERS

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The theme of this symposium has been to delineate key research areas that need to be addressed in order to establish effective and reliable interaction of humans with automated and robotic systems in future manned space systems. Topics addressed in the earlier sessions included System Productivity, Expert Systems, Language and Display for Human-Computer Communication, Computer-Aided Monitoring and Decision Making, Telepresence and Supervisory Control, and Social Factors in Productivity and Performance. In this final session the speakers have addressed some of the broader issues related to the human role in future space systems.

Professor Starbuck has examined the sharing of cognitive tasks between people and computers and Professor Akin has examined the roles of humans and machines in previous space missions and has considered how these roles may change in the future.

In his paper, David Akin points out that any self contained device performing a useful function in space, whether human or robot, must rely on the same set of basic functions to adequately perform its mission. These include: sensory, computational, manipulative and locomotive capabilities and the environmental support functions necessary for the device to exist. Humans evolved in the environment of Earth's surface and are dependent upon a similar atmosphere and gravitational reference along with food, water and periodic rest/sleep periods. The space support systems for extended-duration manned missions must accommodate these human

needs, perhaps even including a form of artificial gravity if it should prove necessary. On the other hand, machines can be designed to operate under a wide range of environmental conditions. The task which we face is to understand the capabilities and limitations of humans and machines as determined from their past and present roles in space and to extrapolate to the future. Akin presents the thesis that it is not an either/or choice because there are necessary and sufficient roles for both humans and machines and there are significant limitations on both.

Recent space missions have shown that the human operator offers combined advantages of manual dexterity and strength whereas most robotic systems available today are designed to provide either strength (e.g., for positioning large masses) or dexterity, but not both. On the other hand, humans can offer both capabilities. Humans represent excellent adaptive control systems, especially well suited for rapid processing and integration of visual data. They have demonstrated their capabilities in space to move large masses along with the capability for precise psychomotor coordination in delicate mechanical adjustments.

Akin suggests that future research should be planned to produce a meaningful data base on human and machine capabilities and limitations in each of the functional categories. This will lead to a better quantitative understanding of the appropriate roles of humans and machines and will allow system planners to know which tasks are worth automating and which ones will best be done by humans for the foreseeable future. He points out that it is not enough to understand limitations and capabilities of each of the component technologies, but we must also

understand the subtle interactions between the human and the machines to define the appropriate roles of each.

Recognizing that humans and machines may be able to perform the same tasks but may use different techniques in accomplishing them, Akin suggests that we also need to develop appropriate metrics in order to be able to produce meaningful comparisons.

He further points out that almost all of the designs currently proposed for telerobotic systems are anthropocentric tending to duplicate the human form. He suggests that since the human form evolved in a gravity field it may not be the best model for space activities and alternate forms and technologies should be studied.

Akin concludes that: (1) robotic systems are evolving rapidly, (2) both human and robotic systems have strengths and weaknesses; (3) for any future systems the best mixture of each is a time dependent solution; and (4) for the immediate future, the presence of each in space is an absolute necessity for the effective use of the other.

From my personal perspective, the criteria of performance, cost and missions success probability (program confidence based on schedule risk and technological risk) are the principal factors that program managers and system engineers use in selecting the optimum design approach for meeting mission objectives. Much as we may wish it to be otherwise, cost and cost effectiveness will continue to be important factors in designing future systems. I would urge, in addition to the metric comparisons of

performance suggested by Akin, that where possible, indices of relative cost also be provided in order that design engineers may have a basis for ensuring the most cost effective utilization of the human operator in the space system of the future.

William Starbuck, in his paper, reminds us that people are flexible and complex. On one hand, they can change their behavior significantly in response to small environmental changes and on the other hand, they change hardly at all in response to apparently large environmental changes.

Starbuck has very eloquently highlighted the behavioral differences between people and computers and suggests that these differences can also mean that combinations of the two can achieve results beyond the capabilities of either alone. He stresses that in defining important research issues in human-computer systems we should be concerned with achieving the proper balance among the opposing advantages and disadvantages and we must recognize that the dividing lines are fluid and depend heavily upon the evolving state-of-the-art in computer design. Accordingly, Starbuck suggests that space system designers should not depend on general theories but rather test specific implementation concepts with the actual users as subjects.

Starbuck suggests that future research efforts can profitably be directed toward improving the interactions and synergies between people and computers. He suggests five research topics as being especially interesting. These are:

- (1) Fostering Trust between People and Expert Systems: e.g., exploring questions regarding the degree a decision-support systems' knowledge and logical rules should be tailored to each user, and the factors that impact the users trust and acceptance of the computer system.
- (2) Avoiding Overload of Human Controllers: e.g., exploring the delicate balance between information overload, yet keeping the human in the loop by providing sufficient information for the human to respond appropriately when emergencies do arise.
- (3) Anticipating Human Errors: e.g., exploring the basic questions of people monitoring machines or machines monitoring people. Computers that predict, detect and remedy human errors raise issues about who is actually in control. Starbuck asks "When should people have the right to experiment or deviate from their instructions?"
- 4) Developing Effective Interface Languages: e.g., exploring the interactions between social contexts and interface languages. Starbuck points out that for experts, working alone, program design languages may be superior to natural language interfaces. On the other hand in space systems, operators with different cultural and scientific backgrounds may need to talk to each other while interfacing with computers and natural language interfaces may prove more effective.

- 5) Using Meaningful Interface Metaphors: e.g., exploring and establishing the conceptual frameworks that highlight the significant properties of different metaphors and their applications. (Every interface is a metaphor of something.)

Starbuck believes that NASA should develop a sophisticated User Interface Management System that will recognize the needs of different users, allow different users to express their personal preferences, and protect the user's individuality. He points out that in the foreseeable future, space crews will continue to represent an exceptional class of people in abilities, training and experience. This suggests to Starbuck a more immediate need for studies of well trained experienced users, rather than research aimed at describing human capabilities in general.

In providing a frame of reference for commenting upon the human factors research areas identified by William Starbuck and David Akin, we might note that NASA's current Space Station mission model covers a broad range of scientific and technical objectives. This model suggests that as the sophistication of future payloads increases, there will be an accompanying shift in crew support skills and requirements. A transition can be anticipated with the progression of time, from the more physical tasks of orbital assembly and installation to more intellectually oriented work activities.

To more effectively use human intelligence, a better match is required with machine intelligence and with "expert" systems. Work stations must

(1) communicate fluently with humans (speaking, writing, drawing, etc.), (2) assist in interactive problem solving and inference functions, and (3) provide knowledge base functions (information storage, retrieval, and "expert" systems) for support.

Based upon the observations of the preceding speakers it would appear that the research issues related to work-station design would logically fall into three categories. These are: (1) Research on Information Seeking Processes, (2) Research on Information/Data Handling Processes, and (3) Research on Operation Enhancement Processes.

Research programs dealing with Information Seeking Processes should include sensory/perceptual research dealing with all sense modalities as well as continuing visual display development. (Continuing effort is required in the development of visual display formats, inasmuch as it is anticipated that, just as today, 80% of the information required by future space crews will be obtained through the sense of sight.)

I would group Starbuck's five research topics under the subject of Information/Data Handling Processes. In expanding his recommendations for establishing Meaningful Interface Metaphors I would also include, as a related topic, research and development of a Universal User Interface Management System (UIMS). This concept for a software system that handles all direct interaction with the user, potentially for a wide variety of underlying applications, began to emerge in the human-computer interface literature several years ago. The concept involves two main components: (1) a set of tools for developers to use in specifying visual and logical

aspects of the user interface; and (2) a set of run time programs and data bases for actually controlling interaction with the users. Some of the potential advantages of a UIMS would be:

- o Independence of the user interface software and the application software.
- o More intelligent user interfaces.
- o Rapid prototyping capability for use in development.
- o Easier involvement of manual systems and flight crew personnel in user interface design and evaluation.
- o Consistency across applications.
- o Multiple user interfaces to the same application if desired (e.g., novice vs. expert modes of interaction)
- o Device independence (i.e., application software does not have to know anything about what type of input device a request came from or what type of output device the results will be displayed on.)

Although Starbuck does not avocate research aimed at describing human capabilities in general, I can't help but believe that continuing research on the nature of human cognition can provide insights that will lead to the development of work stations permitting more effective use of human

cognitive capabilities. Conversely, studying the best and brightest representatives of the user community as they interact with the evolving concepts of expert systems, may in turn provide insights toward defining a structure of human intellect for mankind in general.

Research on Operation Enhancement should include those research areas identified by Akin such as intelligent robotics, and the mechanization of effector/actuator systems.

In addition to research dealing with Information Seeking, Information Handling, and Operational Enhancement Processes continuing attention also should be directed to the development of assessment techniques. These might include such areas as:

- o Measurement of Human Productivity; i.e., continuing effort to develop valid measures of human performance and productivity in order to have meaningful criteria for evaluating performance and productivity adjustments caused by changes in operational procedures and system design concepts.
  
- o Critical Incident Analyses of Human Performance; i.e., continuing effort to investigate and understand the cause of "human error" in space system operations, as well as incidents of exceptional performance, in order to identify and classify the causal factors of exceptional performance, in order to identify and classify the causal factors and establish guidelines for the designing of future space systems.

In closing this session on the human role in space, we can perhaps gain some perspective on the future research needs by looking at the lessons learned in previous manned space missions. We have learned from the US and Soviet<sup>1</sup> space programs to date that (1) systems can have indefinite operational lifetimes in space if they are designed to permit the contingency of in-flight repair and maintenance; (2) structures too large to be launched intact can be constructed and assembled on orbit, using man's unique capabilities; and (3) the flexibility and creative insights provided by the crew in situ significantly enhance the probability of successfully achieving mission objectives.

Reflecting upon their experiences as crew members of the Spacelab-1 mission, Garriott et al. (1984) succinctly described their activities in space by describing three levels of crew participation in accomplishing the mission objectives. At one level, the space crew found themselves highly involved in research activities and working together with principal investigators on the ground in the performance and real-time interpretation of research results. This was the case in areas such as space plasma physics, life sciences, and some materials-science and fluid-physics experiments. At another level, the crew found themselves performing other technical tasks with very little ground interaction. This was the case in the installation of cameras on a high-quality window or scientific airlock table and in the verification of their proper performance. At a third level, the specific experiments were largely controlled from the ground with the space crew participating only when

needed to verify experiment performance or to assist in malfunction analysis and correction.

It can be anticipated that future space missions are likely to continue to require human support at each of these levels.

The ability of the crew to manually assemble delicate instruments and components and to remove protective devices, such as covers, lens caps, etc., means that less-rugged instruments can be used as compared to those formerly required to survive the high launch-acceleration loads of unmanned launch vehicles. As a result, complex mechanisms secondary to the main purpose of the instrument will no longer need to be installed for removing peripheral protective devices or activating and calibrating instruments remotely. With the crew members available to load film, for example, complex film transport systems are not needed, and malfunctions such as film jams can be easily corrected manually. The time required to calibrate and align instruments directly can be as little as 1/40th of that required to do the same job by telemetry from a remote location. Even for pure manipulative tasks, experienced operators are found to take as much as eight times longer using dexterous electronic-force-reflecting servomanipulators as compared to performing the same tasks by direct contact.

In future space missions specific experiments and operations no longer will need to be rigidly planned in advance, but can change as requirements dictate. One of the greatest contributions of crews in scientific space missions can be in reducing the quantity of data to be transmitted to

Earth. One second of data gathered on SEASAT, for example, required 1 hour of ground-based computer time for processing before it could be used or examined, or a value assessment made. Before recording and transmitting data, scientist-astronauts in situ could determine in real-time whether cloud cover or other factors are within acceptable ranges.

The astronaut can abstract data from various sources and can combine multiple sensory inputs (e.g., visual, auditory, tactile) to interpret, understand, and take appropriate action, when required. In some cases the human perceptual abilities permit signals below noise levels to be detected. Man can react selectively to a large number of possible variables and can respond to dynamically changing situations. He can operate in the absence of complete information. He can perform a broad spectrum of manual movement patterns, from gross positioning actions to highly refined adjustments. In this sense, he is a variable-gain servo system.

Thus, with the advent of manned platforms in space, there are alternatives to the expensive deployment of remotely manned systems, with their operational complexity and high cost of system failure. Long-term repetitive functions, routine computations or operations, and large-scale data processing functions, however, can be expected to be performed by computers capable of being programmed and serviced by crews in orbit, just as they are now serviced in ground installations. In addition, the normal functions of the terrestrial shop, laboratory, and production staff will

find corollary activities in the work done by the crews manning the space platforms of the coming generation.

The human being represents a remarkably flexible and adaptable system. In terms of his basic capabilities and limitations, however, we must also remember that man is essentially invariant. In terms of basic abilities, people will not be much different in the year 2050 than they are today. Recognizing this constancy in sensory, perceptual, cognitive, and psychomotor abilities, the objective of the proposed research programs should be to improve system productivity through (1) hardware, software, and other system improvements that can enhance human performance, and (2) procedure and operational changes that will allow more effective use of the human element in the man-machine systems of the future.

NOTES

1. The Soviets have been reported to rely heavily on manned involvement in order to repair equipment and subsystems with serious shortcomings in reliable and trouble-free service life.

## REFERENCES

Garriott, O. W., Parker, R. A. R., Lichtenberg, B. K. and Merbold, U.  
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SESSION 7:

THE HUMAN ROLE IN SPACE SYSTEMS

SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

Harry L. Wolbers, Ph.D.

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THE HUMAN ROLE IN SPACE SYSTEMS  
SYNOPSIS OF GENERAL AUDIENCE DISCUSSION

Following the presentations by the invited symposium speakers, the proceedings were opened to discussion and comment from the floor. A synopsis of the remarks made during this period of open discussion is presented below.

Stephen Hall, NASA Marshall Space Flight Center, referring to the apparent lack of acceptance of expert systems by many potential users (mentioned by Starbuck) asked, "Is this a fundamental limitation of expert systems or if not, what can be done to increase potential user acceptance?" In reply William Starbuck of New York University suggested that there are ways to teach people to trust expert systems. Starbuck pointed out that there are factory scheduling programs, for example, that people now trust. Many factory schedulers use such programs but have no idea how they work and couldn't replicate them if they wanted to. After using them for a period of time they learn to accept them. One key to acceptance is that the users learn that even if the computer may not be able to explain how it derived the answers to a problem, it can present the solution and provide an indication of how good it thinks the answer or solution is. Over time, the correlation of predicted and observed results instills confidence in the user.

Guilio Varsi, NASA Headquarters, suggested that not enough attention has been paid to the impact which the degree of media exposure can have on the acceptance and performance of space missions, and raised the question

of the degree to which such exposure is appropriate. He cited the heroic image of the astronauts created to date. He wondered whether they are likely to receive this same degree of exposure in the future and how this exposure or lack of it may influence future performance. Varsi also commented on the issue of mission safety, pointing out that in addition to the criteria of performance and cost, safety - especially as related to human safety - should be of continuing concern. Varsi asked the question "As we move from the heroic to the routine, what is the real level of risk we are prepared to sustain?" As a final point, Varsi commented that many interesting research issues and questions for investigation were raised during the symposium and he suggested that an ordering of these research issues should be provided, highlighting their urgency not so much from the standpoint of priority but rather from the sequencing or logic to be followed in attacking these problems. He asked, "Is there any one research program sequence that offers a more effective path to addressing the critical issues than any other one?"

In reply to Varsi's comments on risk adversity and safety, David Akin of MIT pointed out that, in his experience, NASA is already orders of magnitude more risk adverse than the undersea community, and if anything, NASA is becoming even more so in light of the Challenger accident. Akin suggested that if anything is going to drive people out of space entirely it is being absolutely risk free. The ultimate in risk adversity is for humans not to go into space at all. While robotic devices may appear to expand the options, in reality the considerations of risk adversity apply to equipment as well. Akin pointed out that in deciding to risk a one-of-a-kind \$100 million telerobotic servicer to

service a satellite with an unfired solid rocket motor, the same issues of risk adversity must be raised for the hardware as would be raised for the crew in a manned mission. To put the issue in proper perspective it is necessary to consider risks and risk adversity in space in relation to potential risks and risk adversity in other fields.

Allen Newell of Carnegie-Mellon observed that no matter how dangerous it is, people believe it to be important and still want to go into space. One of the realities which must be faced is that by being so careful for the first 25 years, levels of National and World expectations of safety in space operations are very high and as a Nation we will suffer from that high level of expectation in the future.

Joseph Loftus of NASA Johnson Space Center observed that an airplane that is safe in peacetime is too dangerous to go to war. He pointed out that in an adversary relationship an airplane is needed that is at the peak edge of performance in order to succeed in its mission. Loftus commented that this is an important point when thinking of space operations because space operation is not a venture in isolation - it is a competition. It is an exploration at a frontier and safety standards cannot be set so high that the frontier is forfeited. At this point Session 7 of the Symposium was concluded.

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CONCLUDING REMARKS:

Allen Newell  
Carnegie-Mellon University  
Pittsburgh, Pennsylvania

Thomas Sheridan  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

CONCLUDING REMARKS

Allen Newell

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In my view, three major issues emerge from this symposium:

1. The merging of AI and robotics.
2. The need to consider the human aspects of these AI-Robotic systems.
3. The potential benefits of incorporating the social sciences into the AI-robotic research effort.

Merging AI and robotics appears to be something that NASA has already identified as an important issue. It is, in fact, one of the great intellectual tasks in this part of the scientific world. With the merging of AI and robotics, AI will finally come to deal, not just with the symbolic world, but with interactions with space (the space of three local dimensions, not NASA's outer space): physical devices, movement, real time, compliance, etc.. This will radically change the field of AI. It is a big step, and its success will depend upon developing a real understanding of the nature of intelligence.

Once AI and robotics are welded together, the concerns for the human aspects of these systems must be addressed along with the concerns for the AI-robotic aspects. There are three distinct reasons for combining behavioral/cognitive science and AI/computer science in a single research program. First, the field of cognitive science -- including physiological and motor behavior, not just cognitive behavior -- provide major clues about developing effective AI-robotic systems. Second, the combination will allow researchers to address the concerns about human-computer interaction from several perspectives. Third, in order to evaluate the performance of automatic devices, much more needs to be known about human functioning in the tasks-to-be-automated. Human performance can be used as a metric of AI-robotic performance.

Finally, a move by NASA towards the social sciences, to incorporate them into an AI-robotic-cognitive science research program, would be very important in the long run. An area that could benefit from such a combination is communication -- how people use the technology to communicate and interact with that technology and with each other. In this regard, the human-computer interaction field is currently taking tentative steps to become much more socially and communication oriented.

Let me end with a remark about university research efforts. The universities, at this moment, are in an extremely pliant state with respect to developing cooperative efforts with external agencies. "Pliant", in this context, means that they are exploring, in a historic way, how to live with much deeper involvement with the industrial, commercial and government sectors. The ideal of the ivy tower seems far

away indeed, although the concepts of independence and objectivity remain solidly in place. There are real opportunities for NASA to build its research programs in ways that will benefit both NASA and the universities involved.

Immense benefits can be garnered from long range, cooperative research programs established in conjunction with places like universities. A ten to fifteen year research relationship between NASA and a university might be expected to yield important dividends beyond the actual research accomplished. The university researchers come automatically to think in terms of NASA and its problems when developing (or expanding) their own research programs. Graduate students, raised in the NASA-oriented research environment, will have an ingrained concern for NASA problems -- and are likely to make a career of dealing with those types of problems. These aspects, though not the stuff out of which research contracts can be made, can be of the highest importance to efforts such as inhabiting space that stretch out into the far future.

CONCLUDING REMARKS

Thomas Sheridan

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The first thing I want to do is thank the speakers. We really appreciate the efforts you have put in. I also thank the organizers. A lot of effort went into getting this together. And I thank the participants -- many useful and interesting comments have come from the floor. Our job, now, is to put together a report that makes sense, is not self-serving, in terms of 'please, Ma, send more money', but says, in effect, 'look, there are some really important research issues out there that are not receiving proper attention'.

I was taking notes, and some of my notes have little stars to indicate important points, for example:

- o The idea of monitoring physiological state of the operator, as well as monitoring the computer and the mechanical state of the equipment was suggested. It seems to me that continually assessing the health of both is something that we don't still quite know how to do.
  
- o There were a number of issues related to the difficulties of defining, and measuring, system productivity. At the very beginning, Ray Nickerson, addressed these issues. Bob Williges insisted that performance is a relative measure.

- o Bruce Buchanan and Thomas Mitchell talked about the reality of non-numerical constraints. AI people have known this all along, but some of us other engineering types haven't particularly appreciated the importance of coping with those non-numerical, or qualitative, aspects of time, space, and resources. They also pointed out the problems of maintaining expert systems as situations change and new knowledge becomes available.
- o Allen Newell characterized the trade-off between knowing versus searching, a priori knowledge versus getting new knowledge (somewhat related to the problem of optimal stopping in operations research).
- o Robustness was mentioned many times, but we are not always clear what robustness implies.
- o We heard about the difficulties of eliciting (and the need for a better "bedside manner" for eliciting) knowledge for the construction of expert systems.
- o We also heard some questions raised about trust. I've looked in the literature on trust and there "ain't much there". We need to understand trust and transparency and that kind of thing vis-a-vis the relationship between intelligent systems and their users.

- o Phil Hayes emphasized the graphical interface and how basic that is to the way people see, think, and make decisions. Peter Polson mentioned the fact that we are now able to, as the pilots say, "kill ourselves with kindness" -- that is, provide graphic displays and "aids" that are so complicated that nobody understands them. This certainly could happen with expert systems. Randy Davis picked up the same point when he talked about designing to make understanding easier.
  
- o Natural language was mentioned time and again, but it was also pointed out that it's no panacea. That there may be languages which are not "natural", but which are better for certain applications.
  
- o Baruch Fischhoff talked about the need for shared models and the fact that people are not very well calibrated with respect to other people's questions and models of reality.
  
- o We talked about the mechanical work, "manipulation". It also was pointed out that we need better models of (and notation for) characterizing the process of manipulation.
  
- o Allen Newell suggested that we need a theory of presence. We know a little bit about the effects of fidelity in simulators from this point of view, but we need a much better understanding of what it means to feel "present".

- o Karen Cook talked about computer-mediated communication, which we are going to have one hell of a lot more of than we have had in the past. We are not going to have situations where people are holding hands; they are going to be separated, and their communication is going to be mediated by computers. Questions of social stress and contending objectives are going to be aggravated or, at least, changed by computer mediated communication -- and by all this "non-human expertise" that's floating around.
  
- o In the last session, Dave Akin raised questions about the paucity of our human performance database, and what people can do relative to what machines can do. Harry Wolbers picked up on the same point.
  
- o And, finally, a lovely notion, I think, made by Bill Starbuck is the importance of being playful and deviant.

Guilio Varsi asked about prioritizing these ideas. That takes a great deal of wisdom -- but we will try<sup>1</sup>.

There is a further comment that should be made. NASA has been extremely cautious about avoiding the risk of errors in space, especially when human life is concerned. This caution is vary laudatory. Where human safety is not an issue, however, there can be more risk taking with respect to such areas as budgetary considerations, testing of equipment,

and studies on the allocation of functions between people and automation/robotics to derive the best mix based on empirical evidence.

We have seen the evidence of this symposium that the computer scientists and the behavioral and human factors scientists can arrive at a common ground. We believe that this interface is obvious and extremely important for mission success based on the best of both worlds that is superior to either automation or humans used alone. In fact, we don't believe that either one can be used alone successfully at this time or in the future.

In conclusion, I thank you all for trudging through the snow and sleet and for your worth while contributions. I'm sure that it has been useful for all of us.

# HUMAN FACTORS IN AUTOMATED AND ROBOTIC SPACE SYSTEMS

National Academy of Sciences  
Lecture Hall  
2101 Constitution Avenue, N.W.  
Washington, D.C.

January 29–30, 1987

## PROGRAM

### Thursday, January 29, 1987

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- 8:00 Registration
- 9:00 Welcome and Introduction  
Thomas Sheridan, (Chair, CoHF) MIT  
Ray Colladay, Associate Administrator, Office of Aeronautics and Space Technology, NASA Headquarters, Washington, D.C.  
David Goslin, Executive Director, CBASSE, NRC
- 9:15 Keynote Address  
Allen Newell, Carnegie-Mellon
- 9:35 Break
- 9:45 Session 1:  
System Productivity: People & Machines  
Paper: Raymond Nickerson, Bolt Beranek and Newman Labs  
Discussant: Robert Williges, VPI&SU
- 10:45 Break
- 11:00 Session 2:  
Expert Systems and Their Use  
Paper: Thomas Mitchell, Rutgers  
Paper: Bruce Buchanan, Stanford  
Discussant: Allen Newell, Carnegie-Mellon
- 12:30 Break for Lunch
- 1:30 Session 3:  
Language and Displays for Human : Computer Communication  
Paper: Phillip Hayes, Carnegie-Mellon  
Paper: Peter Polson, U. of Colorado  
Discussant: Judith Reitman Olson, U. of Michigan
- 3:00 Break

- 3:15 Session 4:  
Computer Aided Monitoring & Decision Making  
Paper: Randall Davis, MIT  
Paper: Baruch Fischhoff, Decision Research  
Discussant: William Howell, Rice
- 4:45 Open Discussion
- 5:30 Reception in Great Hall

### Friday, January 30, 1987

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- 8:30 Session 5:  
Telepresence & Supervisory Control  
Paper: Thomas Sheridan, MIT  
Paper: Lawrence Stark, U. of California  
Discussant: Antal Bejczy, JPL
- 10:00 Session 6:  
Social Factors in Productivity & Performance  
Paper: Karen Cook, U. of Washington  
Paper: H. Andrew Michener, U. of Wisconsin  
Discussant: Oscar Grusky, U. of California
- 11:30 Break for Lunch
- 12:30 Session 7:  
The Human Role in Space Systems  
Paper: David Akin, MIT  
Paper: William Starbuck, New York U.  
Discussant: Harry Wolbers, McDonnell Douglas
- 2:00 Concluding Remarks and Open Discussion  
Allen Newell, Carnegie-Mellon  
Thomas Sheridan, MIT (Chair)
- 2:30 Adjourn