EFFECTS OF FORCE AND VISUAL FEEDBACK ON SPACE TELEOPERATION; WITH POLICY IMPLICATIONS

by

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Submitted to the Department of Mechanical Engineering
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ABSTRACT

An experimental study was conducted to determine the effects of various forms of visual and force feedback on human performance for several telemanipulation tasks. Six test subjects used the master/slave manipulator in the Man/Machine Systems Laboratory during two experimental sessions. In one session the subjects performed the tasks with direct vision, with and without force feedback, and with the manipulator at three different distances (4, 8, and 12 feet) from the task board. During the other session, the tasks were performed using a video monitor for visual feedback, with and without force feedback, and with three different frame rates (3, 5, and 30 frames/second) for the video transmission. The tasks were three peg-in-hole type tasks corresponding to 4, 5, and 6 bits/task according to Fitts' Index of Difficulty.

The experimental data were analyzed through an analysis of variance. The video viewing results showed that frame rate, force feedback, task difficulty, and the interaction of frame rate and force feedback made significant differences in task times. For the direct viewing environment, viewing distance, force feedback, task difficulty, and the interaction of viewing distance and force feedback made significant differences in task times.

Comparable visual feedback to the human operator was provided by (a) the eight foot distance for direct viewing, and (b) thirty frames/second frame rate for video viewing. This allowed for an analysis between the direct and video viewing environments. While force feedback and task difficulty made significant differences in task times, the view itself (video vs. direct) did not.

The domestic and international policy environment for automation and robotics in space was also investigated. This included the issues of political, economic, and technical feasibility, as well as the impacts on international industrial competitiveness. Policy studies were analyzed and discussed. A strong, long-term policy in support of developing automation and robotics technologies in space was recommended. Such a policy will provide benefits for the U.S. space program and economy.

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LIST OF ACRONYMS AND ABBREVIATIONS

A&R	Automation and Robotics
AIAA	American Institute of Aeronautics and Astronautics
ANL	Argonne National Laboratory
ANOVA	Analysis of Variance
ARP	Automation and Robotics Panel
ATAC	Advanced Technology Advisory Committee
BAT	Beam Assembly Teleoperator
DEG	Degrees
DF	Degrees of Freedom
EVA	Extra-Vehicular Activity
FFB	Force Feedback
FPS	Frames per Second
FR	Frame Rate
FTS	Flight Telerobotic Servicer
GSFC	Goddard Space Flight Center
HUD	Housing and Urban Development
Id	Index of Difficulty
IEEE	Institute of Electrical and Electronics Engineers
IVA	Intra-Vehicular Activity
JEM	Japenese Experiment Module
JSC	Johnson Space Center
LaRC	Langley Research Center
MIT	Massachusetts Institute of Technology
MS	Mean Square
MSC	Mobile Service Center

MSE	Mean Square Error
MSFC	Marshall Space Flight Center
MSV	Mean Square Value
N	Number of Observations
NASA	National Aeronautics and Space Administration
NOSC	Naval Ocean Systems Center
NRC	National Research Council
OAST	Office of Aeronautics and Space Technology
OMV	Orbital Maneuvering Vehicle
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
OTA	Office of Technology Assessment
R&D	Research and Development
RMS	Remote Manipulator System
ROV	Remotely Operated Vehicle
SAE	Society of Automotive Engineers
SFM	Service Facility Manipulator
SSI	Space Studies Institute
STD ERR	Standard Error
TARGA	Truevision Advanced Raster Graphics Adapter
TOL	Tolerance
VA	Viewing Angle

CHAPTER 1 - INTRODUCTION

1.1 RESEARCH NEEDS

Performing a task directly with hands and eyes, unimpeded by physical distance, hardware, or artificial communication, has been observed experimentally to be quicker, easier, and usually more accurate than performing a task remotely using video and a remote manipulator device. However, not all space tasks are well suited to be done manually by astronauts in extra-vehicular activity (EVA) due to the nature of the task, the risks and nature of the space environment, or the astronaut being constrained by his/her gloves or pressure suit. Thus there are safety, cost, and efficiency considerations that can make EVA procedures undesirable. Many researchers and engineers, faced with the necessity of remote viewing and handling, have sought to understand why unconstrained manual performance is quicker, but the answer is elusive. Nevertheless, knowing when to have manipulation tasks done by astronauts in EVA, remote manipulators controlled by humans, or autonomous robots is an important current issue.[1]

Ideally the human operator's performance in telemanipulation needs to closely represent performance in the hands-on environment, and surely this can be improved by providing the operator with appropriate and adequate feedback. Teleoperation will not eliminate or drastically alter the need for humans in space, but it will alter the roles that humans fulfill in space and should improve human productivity there. The use of remote

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[1] Thomas B. Sheridan, "Why Bare Hands Beat Telemanipulators: An Approach to Understanding Why," MIT Man/Machine Systems Laboratory, December, 1986, p. 1.

manipulators should also free up valuable crew time to be spent on other space operations and experiments.

The role of telerobotics in space and how it can and will effect the U.S. manned space program is unclear. Congress has mandated that substantial percentages of the research and development budget for the space station be allocated for automation and robotics. However, many of the capabilities of automation and robotics including human performance when interacting with teleoperators in space are unknown.

International competitiveness issues and the questions of the proper roles of humans in space since the Challenger accident have added to the emphasis on robots and teleoperators in the U.S. space program. As a result, where and how research and development funds should be allocated has also become an important topic amongst space policy makers. These questions have been difficult ones to answer because many research issues regarding remote manipulation are still unresolved, including the importance of various types of force and visual feedback.

The objective of the thesis experiments is to provide information to help technologists and policy makers better understand what the capabilities of humans are when interfacing with telemanipulators under various sensory feedback conditions. Additionally, understanding the policy environment surrounding the use of remote manipulators is essential for the proper implementation of the research results and the use of remote manipulation in space.

1.2 RESEARCH ENVIRONMENT AND METHODOLOGY

The elements of a remote viewing and manipulation system include a video camera, a telecommunication channel, a video display, human eyes, human arms and hands, a master arm, a slave or robot arm, and the task operation itself (such as putting a peg into a hole). These elements have not only desirable but also undesirable properties. They tend to add undesirable forces, displacements, time, illumination, and contrast to the remote environment that would not be there in the manual situation. They can be perceived as "filters" that prevent information from reaching the human operator, and thus retard performance.[2] The effects of various degrees of some of these "filters" were investigated in this thesis. The "filter factors" investigated in this thesis include:

- Force feedback and its effects on motor capabilities.
- Video frame rate, and its effects at different values on performance.
- Viewing distance (retinal image size or viewing angle) and its effects on task performance for manipulation with direct viewing.
- Task difficulty and its effects on the cognitive and motor capabilities of human operators.
- The use of a video monitor versus the use of direct vision for remote manipulation.
- The interactions of two or more of the above variables with each other and the corresponding effects on performance.

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[2] Sheridan, p. 2.

These "filters" and their effects need to be identified and quantified to provide information to facilitate efficient teleoperation in space. Experimental findings, quantified and analyzed through statistical methods, should prove helpful to researchers and policy makers alike. The results could be implemented over a variety of space applications. These include:

- space shuttle remote manipulator system
- control of an orbital maneuvering vehicle with a robotic front end
- telerobotic servicer on the space station
- a number of planetary and lunar missions such as a Mars sample return mission or lunar exploratory operations.

1.3 THESIS GOALS

In summary, this thesis has two goals:

1) Determining the effects of varying forms of visual and force feedback on human performance in using space teleoperators.

2) Investigating the space policy environment for the use of robots and teleoperators in space to understand how telemanipulators could be implemented in space operations to benefit the U.S. space program and the U.S. economy.

CHAPTER 2 - SPACE TELEOPERATION: BACKGROUND & APPLICATIONS

2.1 TELEOPERATION DEFINITIONS

Antal K. Bejczy of the Jet Propulsion Laboratory (JPL) defines teleoperation as the use of robotic devices having mobility, manipulative and some sensing capabilities, and remotely controlled by a human operator.[1] NASA has defined a teleoperator system as a remotely controlled, cybernetic, man-machine system designed to augment and extend man's sensory, manipulative, and cognitive capabilities. NASA does not intend for these systems to replace humans in space, but rather have these systems augment the capabilities of humans in certain scenarios and present alternative approaches for various space operations.[2]

The prefix "tele" suggests the tendency to control remotely. Teleoperator refers to mechanical vehicles or manipulator arms that are remotely controlled by a human operator. Stereopsis in the visual feedback and tactile and force feedback through the manipulator arm can add to the ability to feel as if one is actually at the remote site, giving way to the term "telepresence." Teleoperation has recently seen many applications in space, undersea

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[1] A. K. Bejczy and K. Corker, "Automation in Teleoperation from a Man-Machine Interface Viewpoint," AIAA/NASA Space Systems Conference, Costa Mesa, CA, June 5-7, 1984.

[2] Stanley Deutsch and Thomas Malone, "The Applications of the Remote Control of the Manipulator in Manned Space Exploration," in Symposium on Theory and Practice of Robots and Manipulators, 1st, Udine, Italy, September 5-8, 1973 (Udine, Italy: International Centre for Mechanical Sciences, 1973), p. 138.

and nuclear environments, and the potential exists for future spillover into mining, construction, and medicine.[3]

Two main areas exist in robotics: industrial robotics and robotic teleoperation. Industrial robots have been used in production environments to perform repetitive work in a structured factory environment. Thus they generally do not require the human qualities of reacting to emergencies and thinking. Conversely, teleoperators utilize mechanical, sensing, and computational techniques to extend the human manipulative, perceptive and cognitive abilities into an environment that is either hostile to or remote from the human operator. Teleoperators generally perform non-repetitive or singular, servicing, maintenance, repair or rescue work with a high degree of unpredictability under a variety of environmental conditions. The involvement of the human operator is necessary, and the human/machine interface and the operator's abilities to interact efficiently with the manipulator systems is a crucial issue.[4] Today's teleoperation technology is based on more than thirty years of research into applied mechanics and dynamics and more than twenty years of research in control engineering, especially servocontrol.[5]

A teleoperator systems designer therefore, faces two major design challenges. First, creating a human/machine interface system that helps the human overcome remoteness and feel like he/she is at the remote location. The second major challenge is to capitalize on the advantages and minimize the inherent disadvantages of having a human in

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[3] Thomas B. Sheridan, "Forty-Five Years of Man-Machine Systems: History and Trends," MIT Man/Machine Systems Laboratory.

[4] Antal K. Bejczy, "Human Factors Issues in Space Teleoperation," 2nd Seminar on Human Factors Technology for Next Generation Transportation Vehicles, I.C.T.S., Amalfi, Italy, June 16-20, 1986.

[5] Jean Vertut and Philippe Coiffet, Robot Technology, Volume 3A, Teleoperation and Robotics: Evolution and Development. (Englewood Cliffs: Prentice-Hall, 1984), p. 16.

the loop.[6] Table 2.1 illustrates the varying degrees of human and machine responsibility and activity to be designed in a teleoperation system. The table exemplifies how the roles of a human in the loop can vary according to the environment and level of machine intelligence and capability to perform various tasks.[7]

Table 2.1 - Degrees of Automation of Remote Environment Work Systems

General Concept or Term	Undersea Mode	Space Mode	Observe Environment	Control Vehicle	Manipulate Environment
direct human control	diver	astronaut in EVA	direct	direct	direct
manned vehicle	manned submersible	manned spacecraft	direct plus video, force reflect	in-the-loop remote	in-the-loop remote
teleoperator (with aspirations of telepresence)	conventional ROV	in-the-loop teleoperator	video, force reflect	in-the-loop	in-the-loop
supervisory controlled telerobot	supervisory controlled ROV	space telerobot	computer mediated artificial sensors	human supervised computer	human supervised computer
autonomous robot	autonomous underwater vehicle	autonomous space vehicle	artificial sensing and intelligence	automatic computer control	automatic computer control

Source: Thomas B. Sheridan, "Teleoperators, Telepresence, and Telerobots," MIT Man/Machine Systems Laboratory, Table 1.

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[6] Kevin Corker and Antal K. Bejczy, "Recent Advancements in Telepresence Technology Development," in Twenty-second Space Congress, NASA Kennedy Space Center, Cocoa Beach, FL, April 22-25, 1985.

[7] Thomas B. Sheridan, "Teleoperators, Telepresence and Telerobots," MIT Man/Machine Systems Laboratory.

Position and force feedback are reconstructible to a large degree in teleoperation, but recreating the visual image as feedback to the operator has been more challenging due to the loss of information (such as stereoscopic vision) when viewing a television monitor.[8] There has been discussion amongst researchers as to whether stereo vision or the operator's ability to change viewing angle of the object being manipulated is more important in reducing performance times.[9] Delays in the transmission line can make force feedback undesirable because of inherent instabilities. However the value of force feedback in many telemanipulation operations is still unknown. Additionally, due to limited bandwidth and transmission line capabilities, the amount of information that can be fed back to the operator in visual or force feedback is restricted. Therefore there is a great need to better understand and quantify the value of the different types of information feedback. This thesis hopefully will shed some light on some of these important questions.

2.2 TELEOPERATORS IN NUCLEAR AND UNDERSEA ENVIRONMENTS

Applications for teleoperators were first developed for the nuclear industry, due to its potentially hazardous environment and need for human interaction. As the demand for work on radioactive materials grew so did the need for remote handling systems. From 1947 until the late 1960's Raymond Goertz and his team at the Argonne National Laboratory (ANL) developed the first teleoperator systems. The ANL team's objective was to develop systems which could perform remotely the types of manipulation and handling

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[8] Vertut and Coiffet, p. 18.

[9] Rene Miller, personal conversation, March 28, 1988.

tasks that would normally be performed by humans on-site if the radioactivity was not present.[10]

Two basic types of manipulators were developed: unilateral manipulators without force feedback, and later bilateral manipulators with force feedback from the remote site to the human operator. The principles and techniques developed by these researchers at ANL are still present in almost all of the teleoperation equipment of today. In 1954 the first master-slave manipulator with force feedback and bilateral electrical servocontrol was developed. This manipulator was the precursor to the E2 master-slave manipulator that was developed at ANL, and used in the thesis experiments. Work in the U.S. continued through the fifties and sixties while the Europeans, most notably Jean Vertut of the CEA in France, also conducted important work in this field.[11] These researchers provided the seminal work that has now evolved into a world wide effort developing advanced manipulator systems for a number of applications in various environments.

Today work continues in telerobotic applications for the handling of radioactive materials in the nuclear industry. For example, the Oak Ridge National Laboratory (ORNL) has been involved in developing new teleoperator and telerobotic systems for the past decade. Their recent programs include the development and demonstration of teleoperators for nuclear fuel cycle applications.[12]

Following the initial emphasis in the nuclear industry, applications were developed for the undersea environment. In 1961 an experimental manned submarine called the

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[10] Ray Goertz, "Some Work on Manipulator Systems at ANL: Past, Present, and a Look at the Future," ROSE Seminar, 26-27 May 1964.

[11] Vertut and Coiffet, p. 26-34.

[12] J.N. Herndon, and William R. Hamel, "Telerobotic Technology for Nuclear and Space Applications," prepared for the U.S. Government under contract No. DE-AC05-84OR21400.

Bathyscaphe Trieste, was equipped with a telemanipulator and controlled unilaterally from a keyboard. Since 1963 the U.S. Navy has sponsored many underwater teleoperation projects most notably programs that developed manipulators and unmanned cable-controlled vehicles. Today almost all small manned submarines used for the construction and maintenance of underwater offshore oil facilities are equipped with unilateral controlled manipulators, and to a lesser degree force reflecting servo manipulators for underwater applications are also available. The Office of Naval Research (ONR) and Naval Ocean Systems Center (NOSC) have done underwater teleoperator research and development for many years. The NOSC in conjunction with MIT designed a small mobile vehicle that is controlled by a fine fibre optic cable and based on computer-assisted control.[13]

2.3 SPACE RELATED APPLICATIONS

Most recently, space applications have become the focus of much teleoperator research. There are two types of spaceflight missions: manned and unmanned. Manned spacecraft can utilize a human's natural sensory, manipulative, mobility, communicative, and cognitive capabilities. A human makes a space system more flexible and adaptable in both normal and unforeseen operating scenarios. But this capability also has its costs in man rating vehicles and providing life support and crew safety. Unmanned spaceflight missions also contain some distinct advantages. These include increased human safety, and the endurance, strength, durability, and expendable nature of machines. They also

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[13] Vertut and Coiffet, pp. 35-37.

present cost savings in eliminating the need for crew systems and crew safety in EVA, spacecraft, or the space station.[14]

A remote manipulator system such as the one that exists on the space shuttle combines the advantages of both the manned and unmanned missions making many space tasks productive, economical, and safe. Stanley Deutsch identified four basic applications for remotely manned systems in space:

1 - Knowing more about an area where man is not ready to be sent, for example a Martian sample return mission before a manned Mars mission.

2 - Working in an environment which is hazardous to man such as in EVA or a hostile planetary surface.

3 - Performing tasks that require operational flexibility requirements extending beyond man's capabilities.

4 - Relieving workload on humans or to free humans for higher order mental activities.[15]

Such applications would be present with many spaceflight operations such as those with controlling an Orbital Maneuvering Vehicle (OMV), inspecting spacecraft or space structures, servicing satellites, rescuing crew or spacecraft, and conducting experiments through telescience.

The first U.S. spacecraft to contain remote manipulator systems were the Surveyor landers that were sent to the surface of the moon. Surveyor III was the first such spacecraft to land on the lunar surface and did so in 1967 (see figure 2.1). Its manipulator

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[14] Stanley Deutsch, "Remotely Manned Systems - Augmenting Man's Capabilities in Space Operations," in Remotely Manned Systems: Exploration and Operation in Space, ed. Ewald Heer (Pasadena: California Institute of Technology, 1973), p. 3.

[15] Deutsch, "Remotely Manned Systems," pp. 3-4.

arms took samples of the lunar soil and acquired data on required forces to accomplish these manipulation tasks.[16]

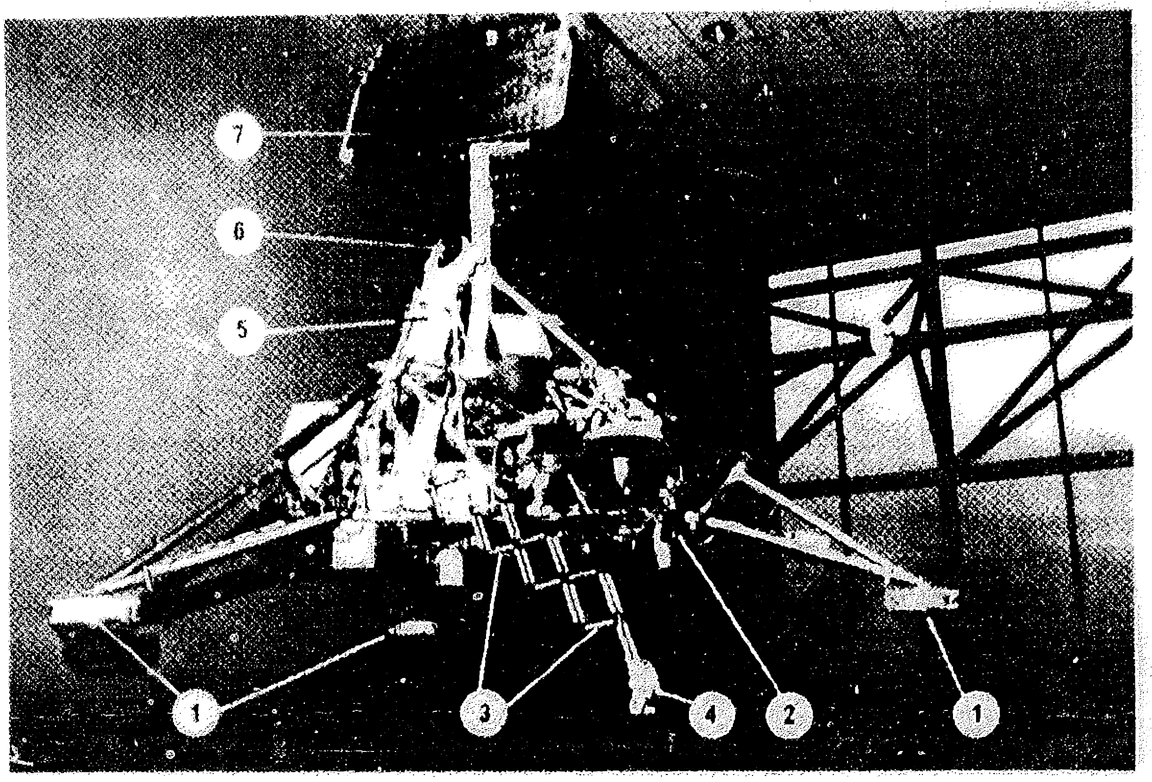

Figure 2.1 - Surveyor, the first spacecraft to perform manipulation on the lunar surface. 1 - feet made from deformable material; 2 - one of the landing nozzles; 3 - manipulator; 4 - shovel instrumented to measure force required to dig small trenches; 5 - television camera; 6 - pan and tilt mirror; 7 - solar cells.

Source: Jean Vertut and Philippe Coiffet, Robot Technology, Volume 3A, Teleoperation and Robotics: Evolution and Development. (Englewood Cliffs: Prentice-Hall, 1984), p.38.

Space teleoperation for remote manipulation in many cases has one major disadvantage: the transmission time delay between Earth or the local spacecraft and the remote spacecraft. Delays have been shown to cause huge performance degradations

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[16] Ewald Heer, "Remotely Manned Systems for Operation and Exploration in Space," in Symposium on Theory and Practice of Robots and Manipulators, 1st, Udine, Italy, September 5-8, 1973 (Udine, Italy: International Centre for Mechanical Sciences, 1973), pp. 152-155.

which have been combated and partially alleviated through research into supervisory control. Supervisory control contains machine intelligence locally and remotely and the human operator provides initial instructions which are the interpreted by the computer to carry out the operation. Therefore the operator acts as a supervisor of the remote operation.[17]

An example of supervisory control in a space mission occurred in the summer of 1976 when the Viking spacecraft landed on Mars and carried out automated manipulation tasks (see figure 2.2). The thirty minute time delay made pure operator control of the manipulation tasks on Mars impossible, but operator intervention was needed in the case of an emergency. To accommodate this scenario the operator had the capability of introducing a corrective command during the delay in transmission of two times thirty minutes.[18] This brought teleoperation and automated robotics together through an application of the theories within supervisory control.

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[17] Thomas B. Sheridan, "Supervisory Control," in Handbook of Human Factors/Ergonomics, ed. G. Salvendy (New York: Wiley, 1986).

[18] Vertut and Coiffet, p. 38.

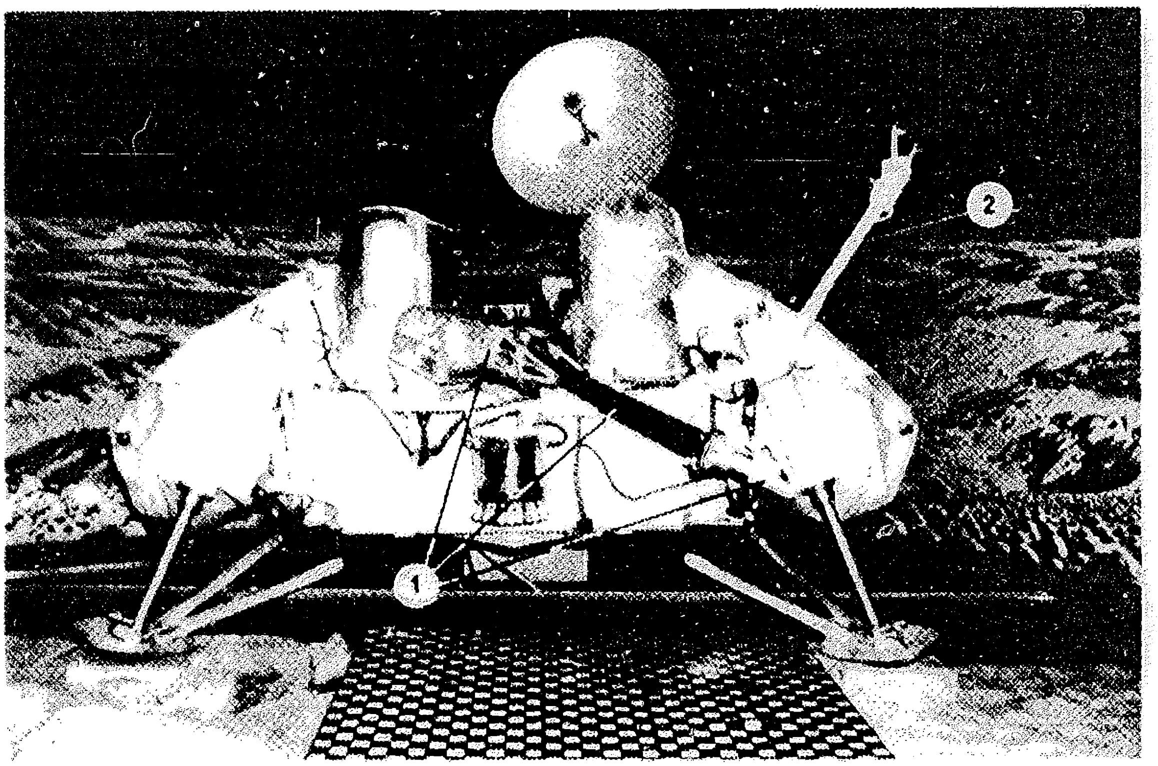

Figure 2.2 - Viking spacecraft: 1 - manipulator and sampler; 2 - arm bearing meteorological instruments.

Source: Jean Vertut and Philippe Coiffet, Robot Technology, Volume 3A, Teleoperation and Robotics: Evolution and Development. (Englewood Cliffs: Prentice-Hall, 1984), p.40.

2.4 CURRENT AND FUTURE SPACE TELEOPERATION

The shuttle has the most advanced teleoperator on a spacecraft in the Remote Manipulator System. This system does provide visual feedback either directly or with the use of a television monitor, but has little dexterity and does not have any force torque reflection or additional sensory feedback. The RMS is controlled by an astronaut using a hand controller that interfaces with a computer. The design incorporates the adaptive control, cognitive, and visual abilities of humans augmented by some automated implementation through a computer.[19]

Some of the recent accomplishments of NASA sponsored A&R research include: Compliant Robotics with Force Feedback at the Goddard Space Flight Center (GSFC), Sensor Based Control of a Robot Arm at the Langley Research Center (LaRC), the Beam Assembly Teleoperator (BAT) at the MIT Space Systems Laboratory, Computer Vision Research at the Jet Propulsion Laboratory (JPL), and Teleoperator Human Interface Technology at JPL.[20]

Based on past experiences with human/machine systems in spacecraft, it appears to be a good mix to have some degree of automation but to also have a human in the loop to simplify the design, and to make the operations more reliable and flexible. In the future, systems will become more and more automated. But the presence of a human in the system will allow the work being done in space to be conducted more efficiently.[21]

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[19] Aaron Cohen, "Automation and Robotics: Key to Productivity," 36th Congress of the International Astronautical Federation, Stockholm, Sweden, October 7-12, 1985.

[20] Lee Holcomb and Ron Larsen, "Overview of the NASA Automation and Robotics Research Program," Twelfth Annual Meeting of the Association for Unmanned Vehicle Systems, Anaheim, California, July 15-17, 1985.

[21] Cohen.

The motivation behind recent research and development of robotics and teleoperation for space applications has been the pursuit of increased productivity, improved reliability, increased flexibility, higher safety, and increasing the productivity/performance of crew accomplished tasks, some of which are beyond the capabilities of the crew. The planned Space Station[22] (see figure 2.3) has been a technology driver for developing advanced capabilities with space telerobotics. Space Station missions will be of long duration and include telemanipulation and telesciences for:

* science and applications
* Earth and solar system observation
* technology development and demonstration
* commercial laboratories and production facilities
* operational activities such as servicing/maintenance of space station structure including various subsystems
* repair and maintenance of satellites
* support of unmanned platforms
* assembly of the station and large space systems
* equipment transfer
* docking and berthing
* inspection
* remote monitoring[23]

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[22] James M. Beggs, "Space Station: The Next Logical Step," <u>Aerospace America</u>, September, 1984.

[23] Kumar Krishen, "Vision Technology/Algorithms for Space Robotics Applications," SOAR '87 - First Annual Workshop on Space Operations Automation and Robotics, Houston, Texas, August 5-7, 1987.

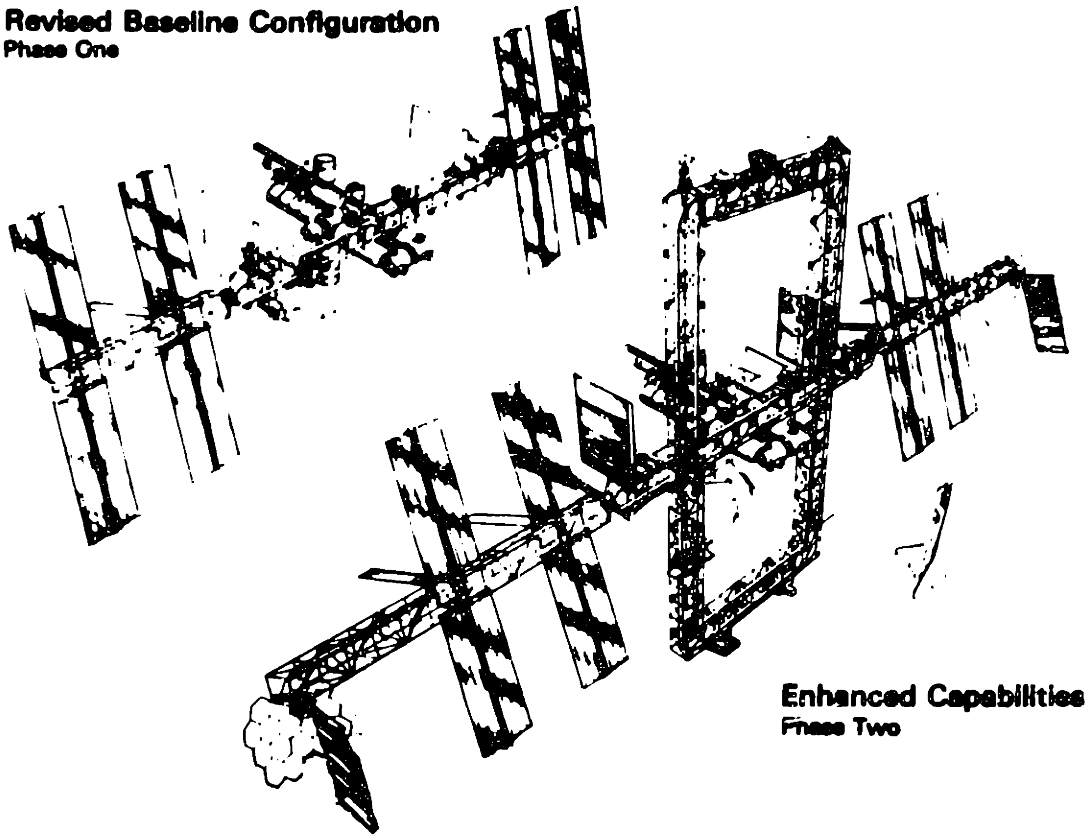

Figure 2.3 - Planned space station: revised baseline and enhanced configuration.

Source: National Research Council, Report of the Committee on the Space Station of the National Research Council (Washington, D.C.: National Academy Press, 1987), p. 12.

On the space station the need to free up crew time to perform commercial or scientific duties will be greater than ever. The proper mix of humans and machines will help provide that needed time. Aaron Cohen, Director of the NASA Johnson Space Center (JSC) has said that the space station will use automation and robotics in three categories:

1) To meet mission needs
2) To provide additional cost and performance benefits
3) To enhance the state of the art[24]

Teleoperation will be needed to provide the ability to perform the space station applications mentioned previously. These tasks will require collision avoidance, dextrous end effectors, and mobility. As an initial application, the space station assembly presents an ideal opportunity to test the capabilities of humans to work with teleoperators in reducing EVA time and increasing productivity.[25]

The telerobotic applications will be carried out with various systems including the current space shuttle remote manipulator system (RMS), the Mobile Service Center (MSC), and the Orbital Maneuvering Vehicle (OMV). The RMS would help with initial station assembly. MSC could handle such tasks as final Station assembly, station/satellite maintenance and repair, and routine inspections. OMV could also be used for the retrieval and repair services. A final step is the development of the Flight Telerobotic Servicer (FTS) that could be used for free-flying inspection, retrieval, and repair tasks.[26]

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[24] Cohen.

[25] Cohen.

[26] Krishen.

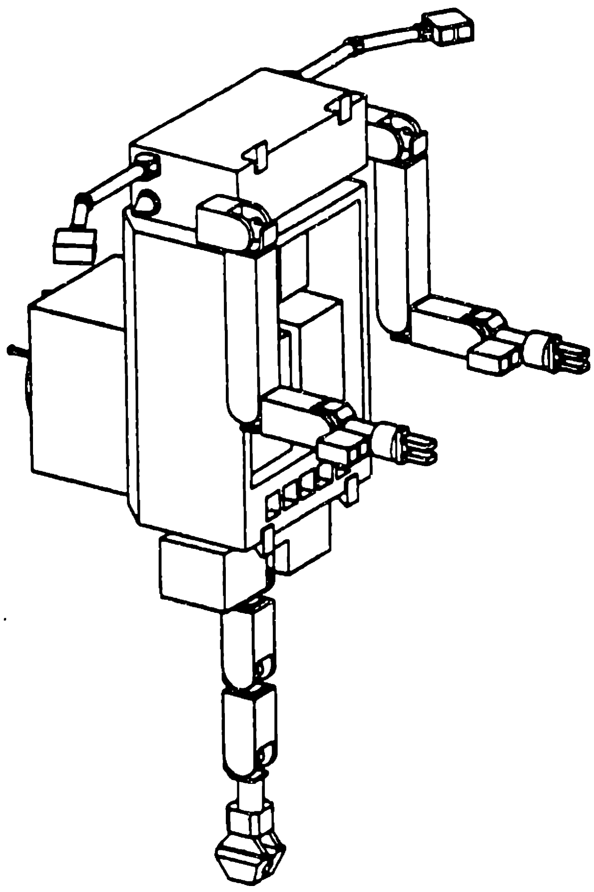

Figure 2.4 - Flight Telerobotic Servicer Concept

Source: Flight Telerobotic Servicer (FTS) Strawman Concept Engineering Report, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD, March 15, 1987, p. x.

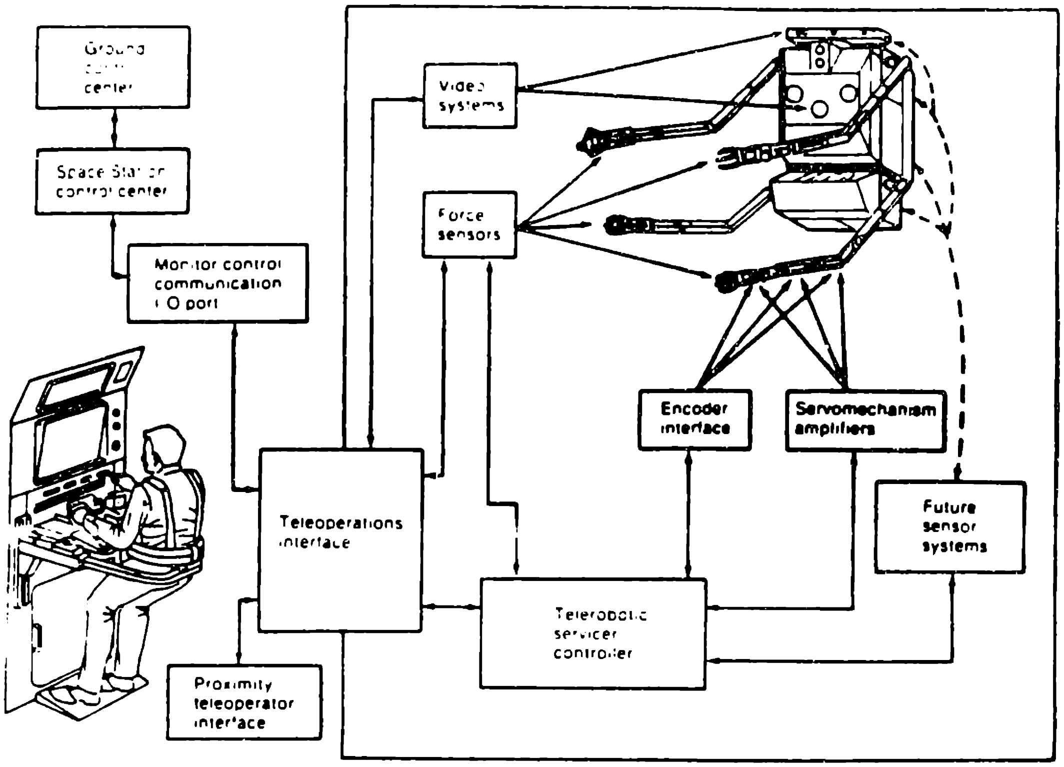

Figure 2.5 - Control concepts for the flight telerobotic servicer.

Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986., p. 21.

The FTS (see figures 2.4 and 2.5) will provide the following benefits for the space station and U.S. industry:

- Reduce EVA tasks and their associated hazards.
- Assist assembly of certain space station elements.
- Assist in space station maintenance.
- Enable more efficient use of crew time as the FTS system becomes more autonomous and teleoperational modes become more capable and sophisticated.
- Expand crew capabilities for maintenance and servicing.
- Provide alternatives to crew involvement with high risk tasks.
- Help current robotics and telerobotics technologies to surpass their present limitations.
- Make advances in telerobotics technology available to the industrial arena.[27]

The FTS will interface with the space station elements (see figure 2.6) to provide the above benefits.

Many of these tasks will incorporate new trends and technologies in teleoperation. These include a continuation of removing the human element away from physical contact with the remote site. This will be accompanied by a growing reliance and confidence in the abilities of remote manipulators to augment the capabilities of humans in space.[28] Work that has incorporated these trends are the telerobotics research and development activities at JPL. Their work has focused on smart sensors, flexible computer controls and intelligent human/machine interface systems that use advanced visual displays and kinesthetic

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[27] Flight Telerobotic Servicer (FTS) Strawman Concept Engineering Report, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD, March 15, 1987, p. 1-8.

[28] Sheridan, "Forty-Five Years."

coupling methods to provide feedback to the human operator.[29] The research efforts in the control of robot manipulators for space tasks at JPL covers every pertinent major technical area necessary to provide for the efficient use of robots and remote manipulators in space.[30]

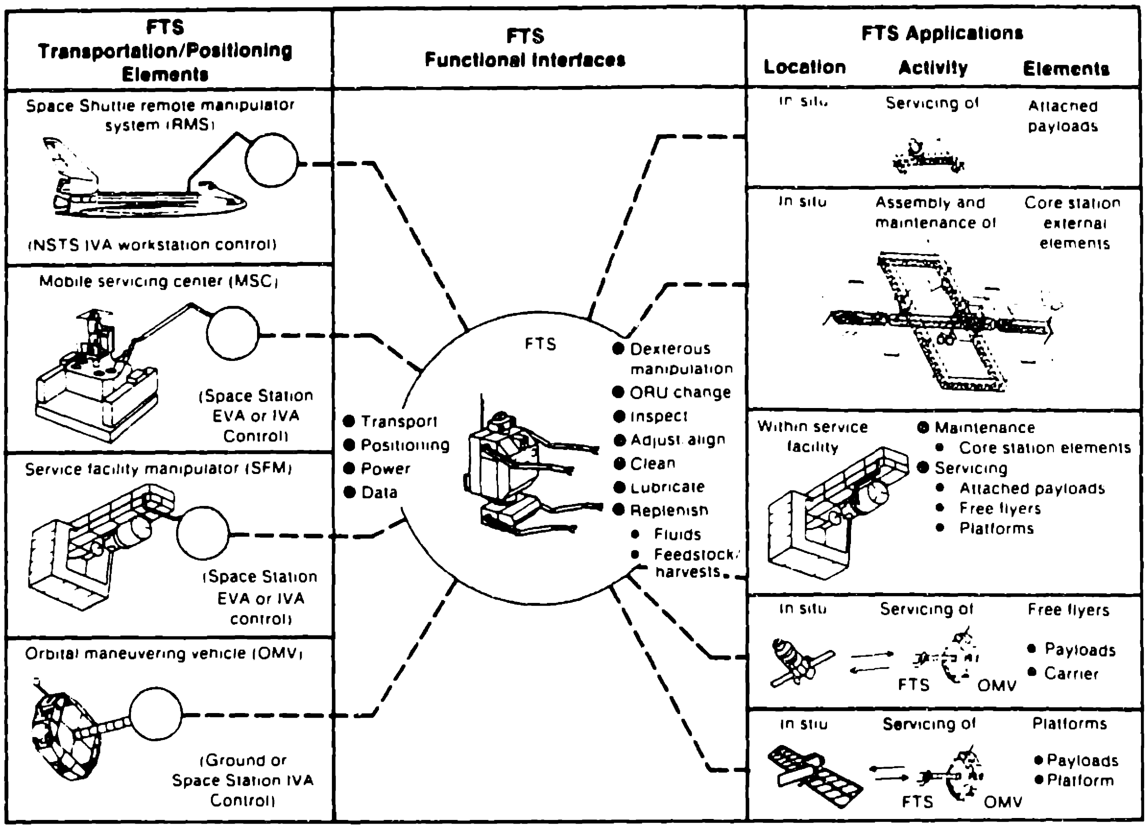

Figure 2.6 - The flight telerobotic servicer interfaces with various space station elements to perform a variety of tasks.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 4, May, 1987, p. 4.

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[29] Antal K. Bejczy, "Distribution of Man-Machine Controls in Space Teleoperation," SAE Technical Paper Series, 821496, Aerospace Congress & Exposition, Anaheim, CA, October 25-28, 1982, p. 15.

[30] Ewald Heer and Antal K. Bejczy, "Control of Robot Manipulators for Handling and Assembly in Space," Mechanism and Machine Theory, Volume 18, No. 1, 1983, pp. 23-25.

A big hurdle that exists is actually building and flying a telerobot in space. Congress has allocated special funding for telerobotic systems on the space station. Three approaches exist for building such a telerobot. The first is to build on existing technology such as the Protoflight Manipulator Arm and the Integrated Orbital Servicing System that were developed in the late 1970's for the Marshall Space Flight Center (MSFC). A second would be to develop an entirely new system. This is currently being done by developers of the Flight Telerobotic Servicer. The third approach is to build a laboratory system that can used at NASA centers and other appropriate locations. This however would reduce time available to build a flight qualified system.[31]

Future research needs include resolved force sensing, touch, kinesthesis, proprioception, proximity sensing, multi-degree-of-freedom end effectors, two-arm interaction, multi-person cooperative control, interchangeable end-effector tools, force-feedback with time delay, and voice control and feedback, among many others.[32] Although the research and development challenges for space telerobotics are substantial they are within the capabilities of the research resources of the nation. Once the constraints of limited time and financial resources are met, there will be sensors and control systems that can produce dexterous, graceful, and skilled behavior in robotic systems. As time goes on, robots will behave more intelligently, taking on more responsibilities and freeing up more

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[31] Jack E. Pennington, "Space Telerobotics: A Few More Hurdles," Presented at the IEEE International Conference on Robotics and Automation, San Francisco, California, April 8-10, 1986.

[32] Thomas B. Sheridan, "Teleoperation, Telepresence, and Telerobotics: Research Needs for Space," Human Factors in Automated and Robotic Space Systems: Proceedings of a Symposium (Washington, D.C.: NRC/NASA, 1987), pp. 279-291.

time for crew members to perform advanced scientific and operational duties.[33] What is needed to make this happen is data on the various capabilities of teleoperated systems and the abilities of humans to interact with them.[34]

All of the benefits and capabilities described in this chapter will be possible only with a better understanding of the capabilities of humans to perform tasks with teleoperator systems, and a better understanding of the policy environment that will drive the R & D of space telerobotics. This thesis will hopefully improve and expand the knowledge base for human performance factors in space teleoperation, and bring the potential benefits closer to fruition.

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[33] James S. Albus, "Research Issues in Robotics," SAMPE Journal, volume 21, January/February, 1985, p. 41.

[34] "Future Research Directions," panel discussion, moderator: G.A. Bekey, Proceedings of the Workshop on Space Telerobotics, volume III, ed. G. Rodriguez (Pasadena: NASA Jet Propulsion Laboratory, 1987), pp. 373-390.

CHAPTER 3 - EXPERIMENTAL EQUIPMENT

3.1 E2 MANIPULATOR SYSTEM

The E2 master-slave manipulator used in the experiments has quite an impressive history. In the late 1940's researchers at the Argonne National Laboratory (ANL) were working on the development of force-reflecting servos. Their goal was to develop manipulators that could not only have the output at the remote site depend on the input signals from the human operator like the manipulators already being used, but also have the input load at the operator's work station be equal or proportional to the output load at the remote location. The E2 is one of the first electric master-slave manipulators that included force-reflecting servos.[1]

To measure the effects of force feedback on manipulation performance in these thesis experiments, performance with force reflection (or force feedback) was tested against performing tasks without force feedback. This was made possible by the E2's capability of operating with direct electronic coupling control both bilaterally with force feedback, and unilaterally without force feedback coming from the slave back to the master arm. The E2 of the Man/Machine Systems Laboratory is displayed in Figure 3.1.

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[1] Raymond Goertz, "Some Work on Manipulator Systems at ANL -- Past, Present, and a Look at the Future," prepared for ROSE Seminar, 26-27 May 1964, pp. 6.1-7.1.

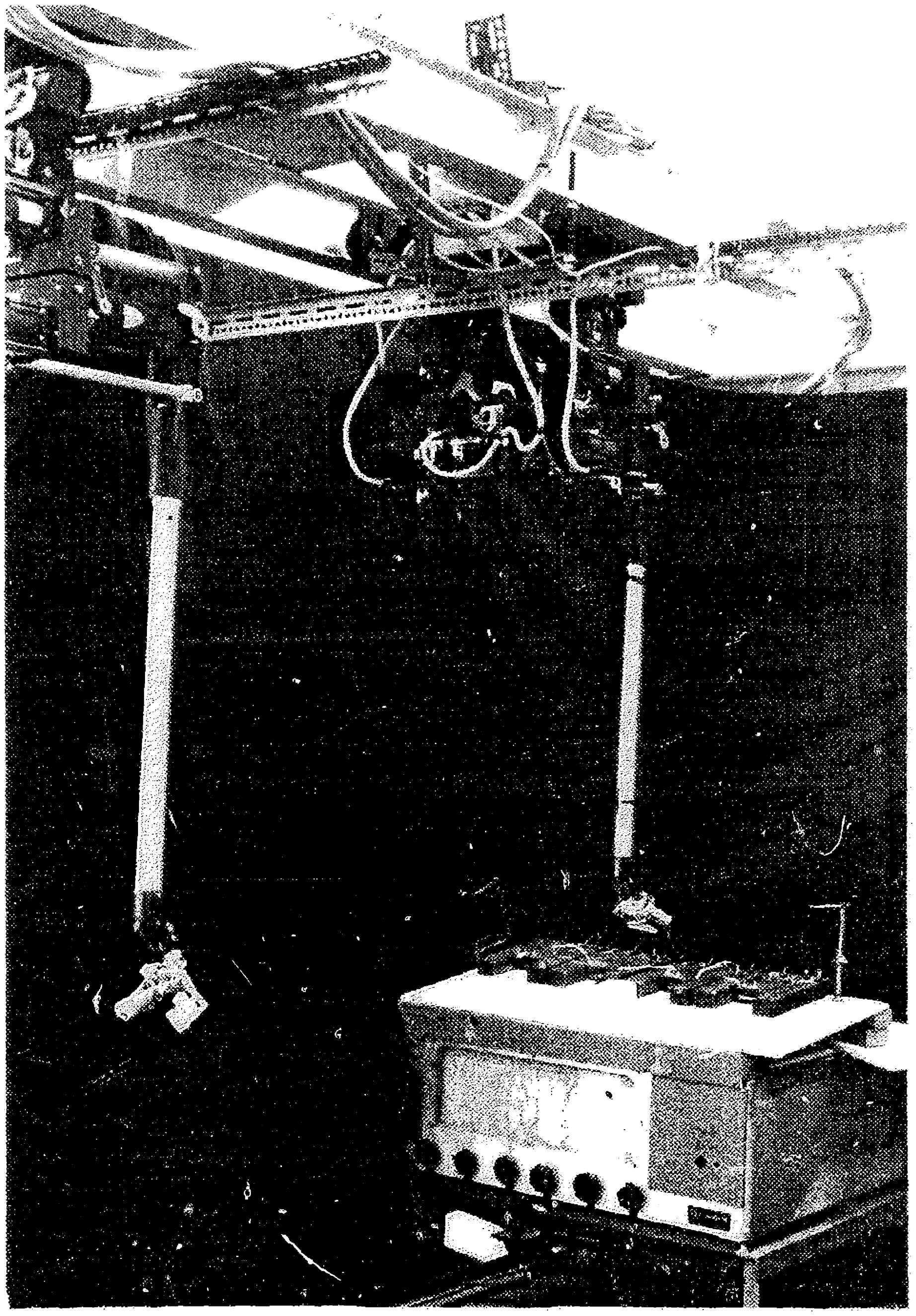

Figure 3.1 - E2 Manipulator System in the MIT Man/Machine Systems Laboratory.

The E2 is right handed, as were all of the test subjects used in the experiments. Both master and slave arms have seven degrees of freedom including end effector gripping, are geometrically similar, and are kinematically isomorphic to the operator's arm and hand. The manipulator degrees of freedom are shown in figure 3.2, and its dimensions are displayed in figure 3.3. As can be seen in these diagrams, the E2 possesses seven degrees of freedom: three (x, y, and z direction) for arm translation, one for arm rotation (azimuth), one for gripper elevation, one for gripper twist, and one for the grasping motion of the gripper jaw. Tracking time delays were considered negligible during the experiments due to the manipulator's quick and accurate response to the operator's input motions.[2]

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[2] James Hampton Black, Jr., "Factorial Study of Remote Manipulation with Transmission Time Delay," MIT Masters Thesis, December, 1970, p.12.

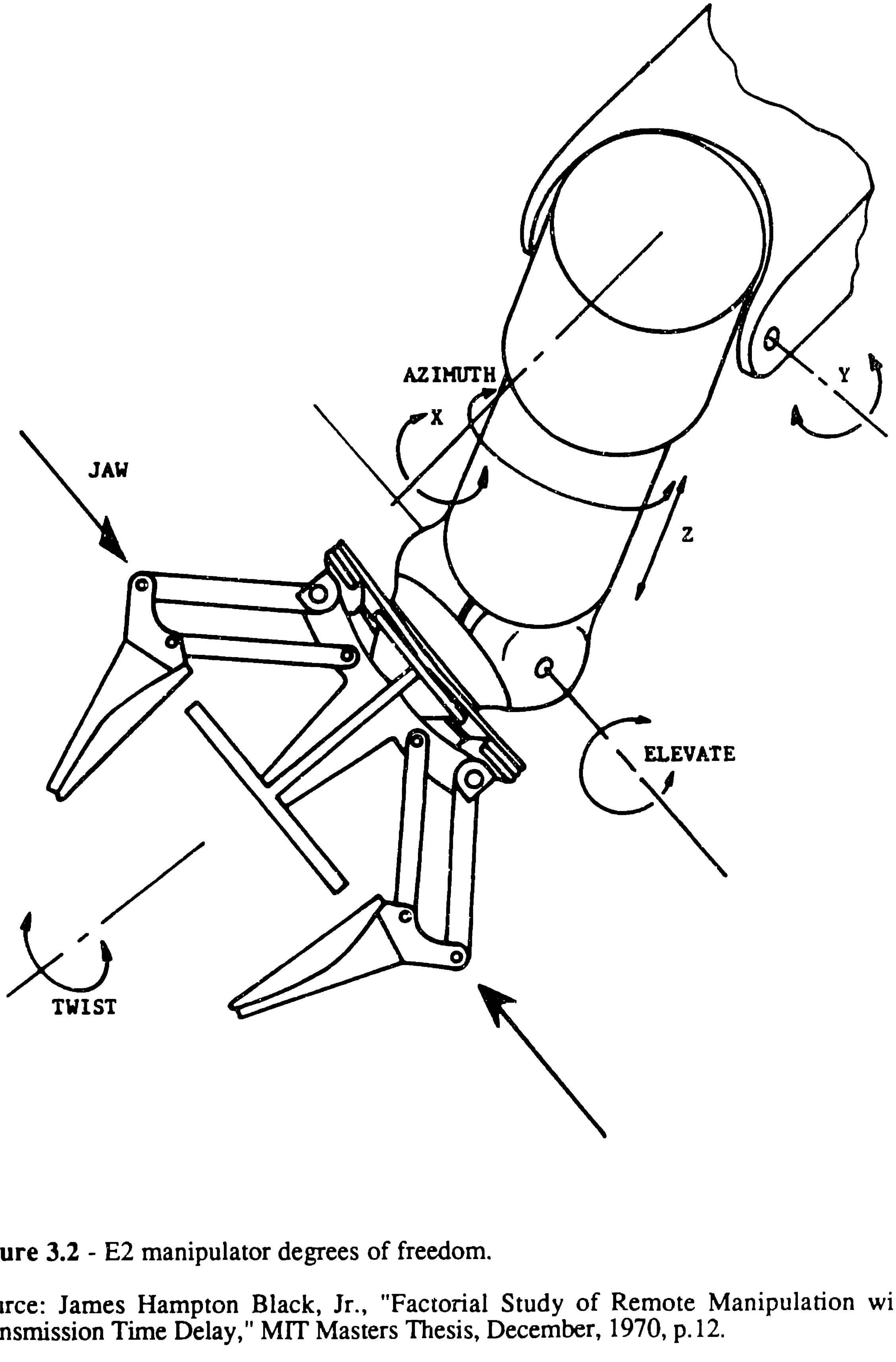

Figure 3.2 - E2 manipulator degrees of freedom.

Source: James Hampton Black, Jr., "Factorial Study of Remote Manipulation with Transmission Time Delay," MIT Masters Thesis, December, 1970, p.12.

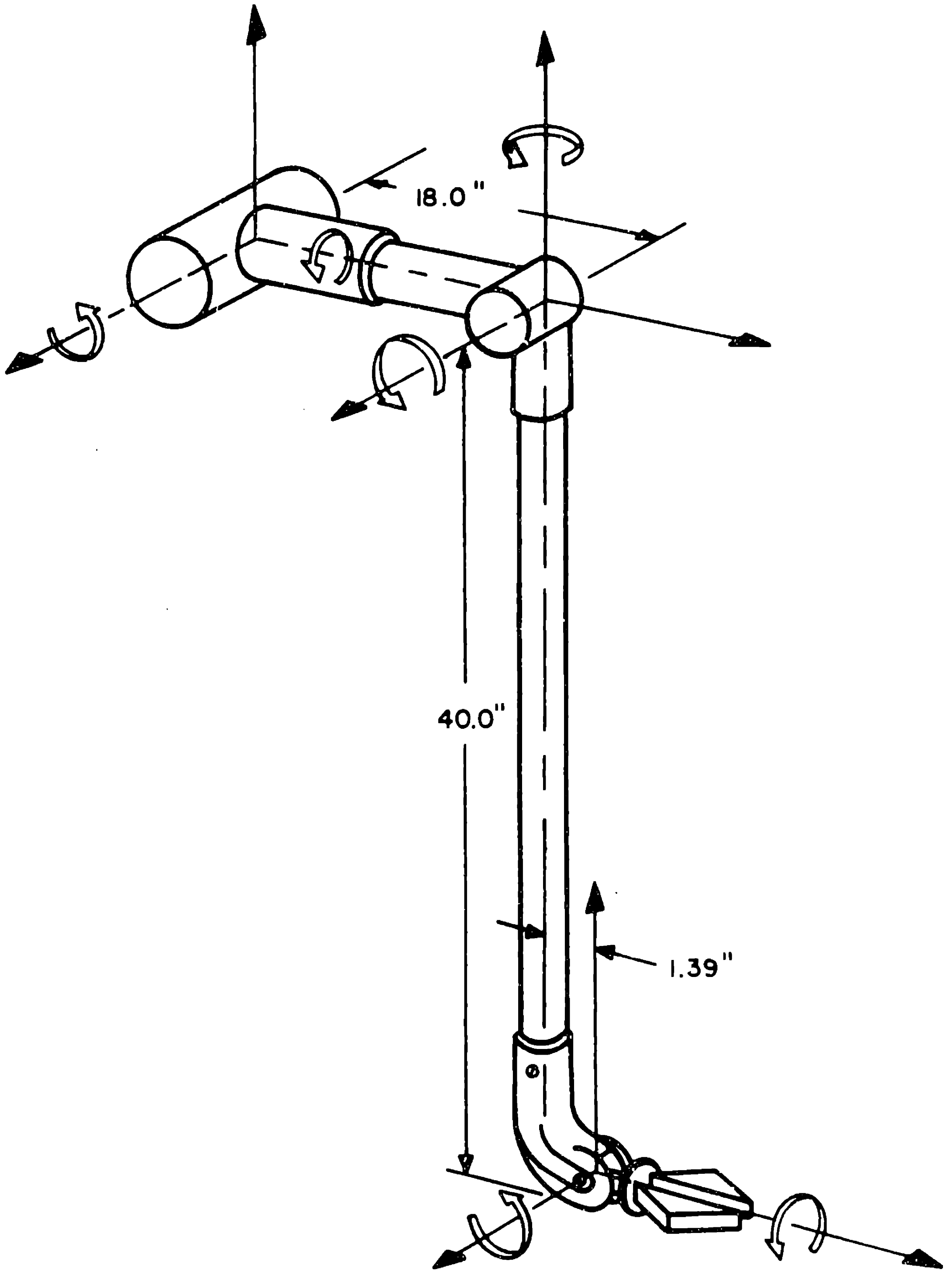

Figure 3.3 - E2 manipulator dimensions and degrees of freedom.

Source:R.C. Groome, "Force Feedback Steering of a Teleoperator System," MIT Master's Thesis, August, 1972.

3.2 VIDEO SYSTEM

The vision system for the video section of the experiments consisted of several components:

1) Sony Trinitron Color Video Monitor PVM -1910
2) Panasonic Color TV Camera WV-3320
3) Panasonic Color TV Camera Control Unit WV-3301
4) AT & T Personal Computer
5) AT & T Truevision Advanced Raster Graphics Adapter (TARGA 16)

The Sony Monitor was connected directly to the PC and received its image signal from the TARGA board inside the PC. The TARGA board produced a picture on the monitor 14 inches wide by 10 inches high.

The TARGA board inside the PC received the video input from the camera control unit which was directly attached to the video camera. The camera contained a TV zoom lens and was mounted on a Stitz tripod approximately sixty five inches above the ground. The camera was also placed at a slight angle looking downward toward the task board.

Central to altering the video environment was the capability of varying the framerate. This was accomplished through the use of the AT & T Truevision Advanced Raster Graphics Adapter (TARGA 16) board and a computer program written by James Roseborough of the MIT Man/Machine Systems Laboratory. TARGA 16 can provide a spatial resolution of up to 512 by 482 pixels with 16 bits per pixel. It captures images in real time: 1/60th of a second per field or 1/30th per frame. The resolution selected for the experiments was 512 X 256 in order to have non-interlaced video input or output. A resolution 512 X 482 was possible but was not selected because it only allowed the interlaced mode. Non-interlaced was chosen because it does not refresh a new frame on top of the image of the previous frame. Interlacing was observed to refresh the screen with a new frame on top of an old one during preliminary experimentation. At low frame rates, this made viewing disproportionately difficult because the old frame would seem to linger and a shadow image occurred.

The TARGA board was set to read one frame every sixtieth of a second. A framerate was selected and the TARGA board would capture a frame at the rate necessary to provide the requested framerate. For example if thirty frames per second was selected the TARGA board would capture a frame ever other cycle, i.e. every thirtieth of a second rather than every sixtieth of a second. When 3 frames per second were input it would grab a frame every 20 cycles or every third of a second.

Figure 3.4 is a photo of the system, and figure 3.5 shows a schematic of how the vision system was connected.

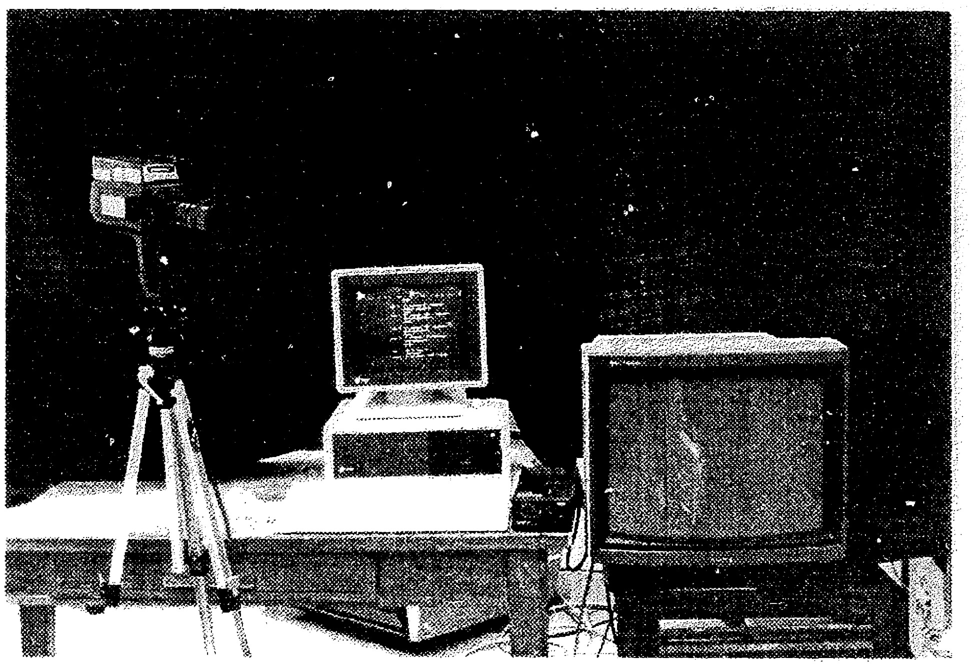

Figure 3.4 - Video equipment.

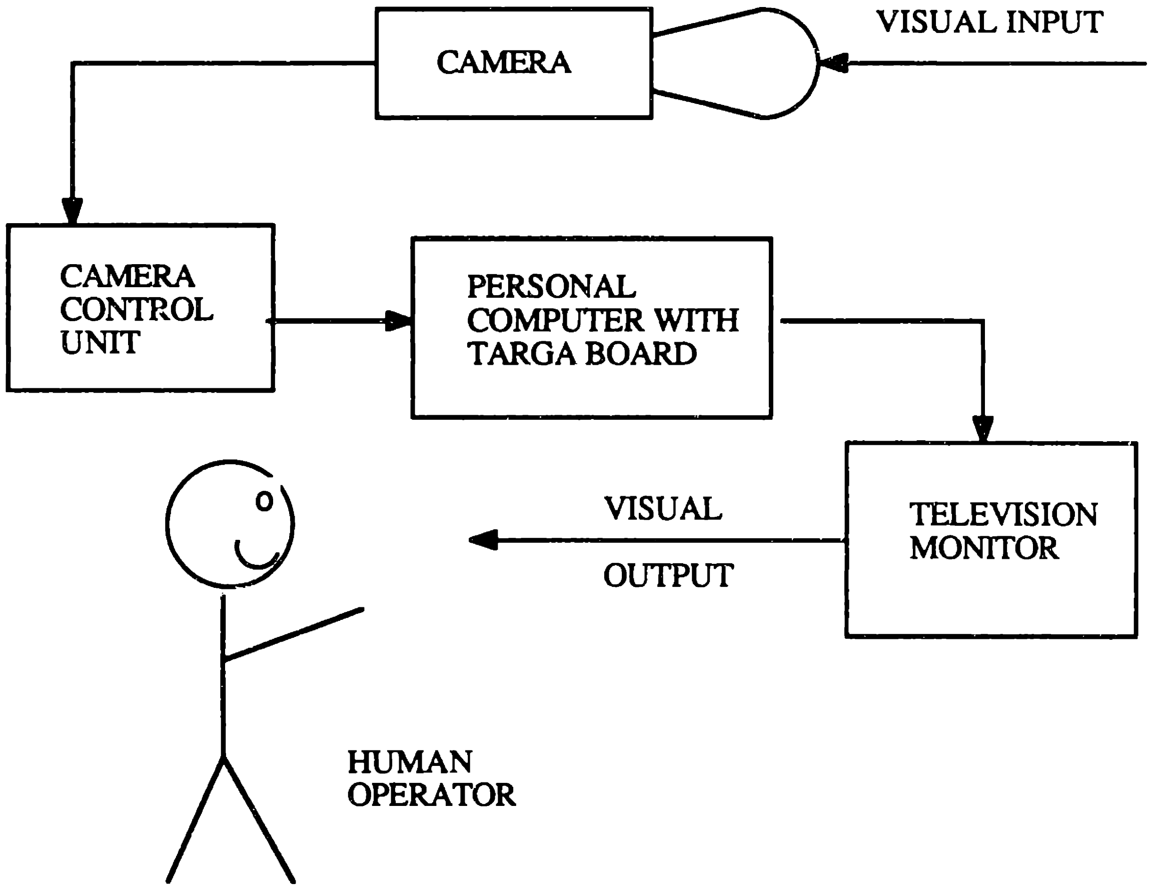

FIGURE 3.5 - VIDEO SYSTEM SCHEMATIC

3.3 TASK BOARD

The task board consisted of three slots and a block. Each slot was made with two side boards and a center board that formed a back. The slots were one and a half inches high, and 2.8 inches deep. Dimensions of the wooden block used the experiments were 2.75 inches in width, 1.5 inches in height, and six inches in length. Figure 3.6 provides a photograph of the task board and block and figure 3.7 displays the slot and block dimensions.

As displayed in figure 3.7 the two end slots were 3.75 inches wide and the middle slots were 3.25 and 3 inches wide respectively. This provided task tolerances from left to right of one inch, one-half inch, one-quarter inch, and one-inch. The centers of each of the four slots were eight inches apart. The selection of these tolerances and distances is discussed further in Chapter 4. Mounted on the lower portion of each center block were limit switches that controlled the clock to record the task times (see section 3.4).

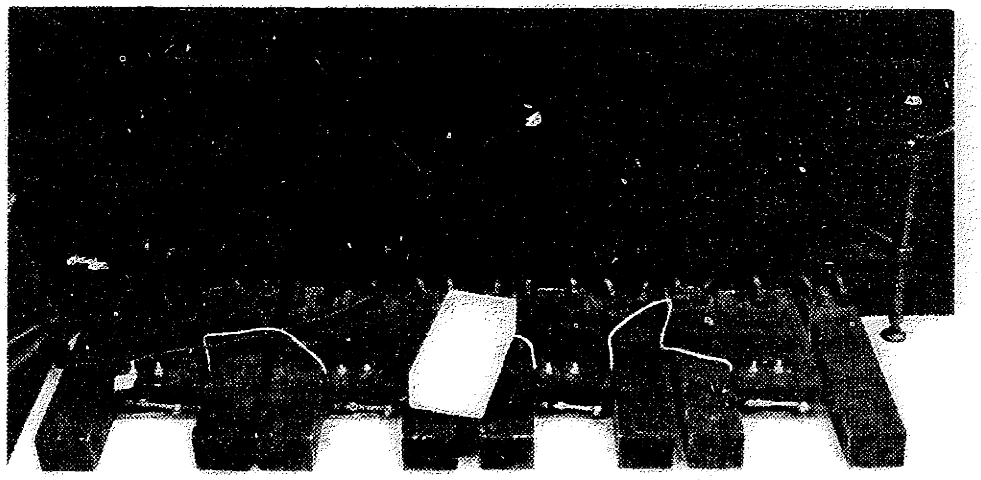

Figure 3.6 - Task board and block

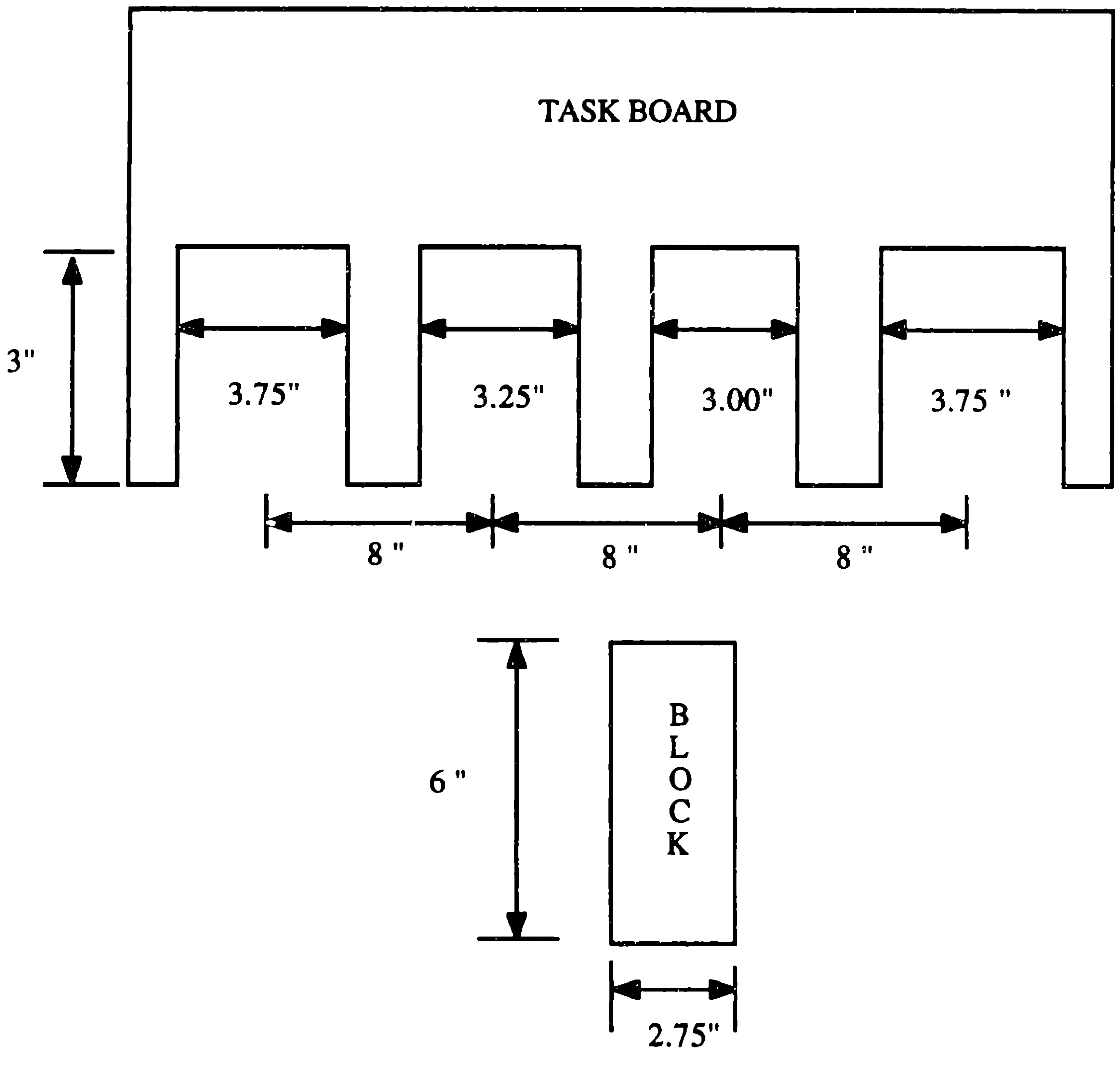

FIGURE 3.7 - TASK BOARD LAYOUT

3.4 TIME RECORDING SYSTEM

A General Electric analog clock that provides time readings to the hundreds of seconds was used to measure the task times. Tasks times were recorded by using limit switches attached at the back of each slot, in the center, and in a low position so the switch could not be contacted unless the block was directly inserted into the slot. The edge of each limit switch was 2.8 inches away from the entrance of the slot, requiring that the six inch long block be slightly less than one half inserted into the slot. Therefore, enough of the block was exposed from the slot to provide a strong grip on the block with the manipulator.

The clock would operate when the block was not making contact with a switch and would stop operating when the block was in contact with a switch. The switches were connected in series. The clock was powered by AC power source and a power switch and a test switch were installed on the clock. Figure 3.8 is a photograph of the system and figure 3.9 displays a schematic of the time recording system.

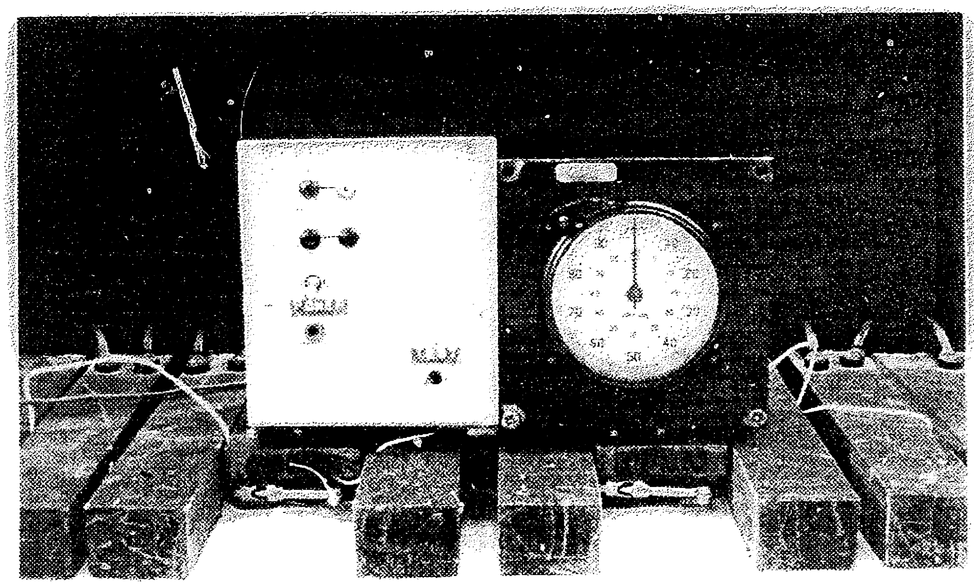

Figure 3.8 - Time recording system.

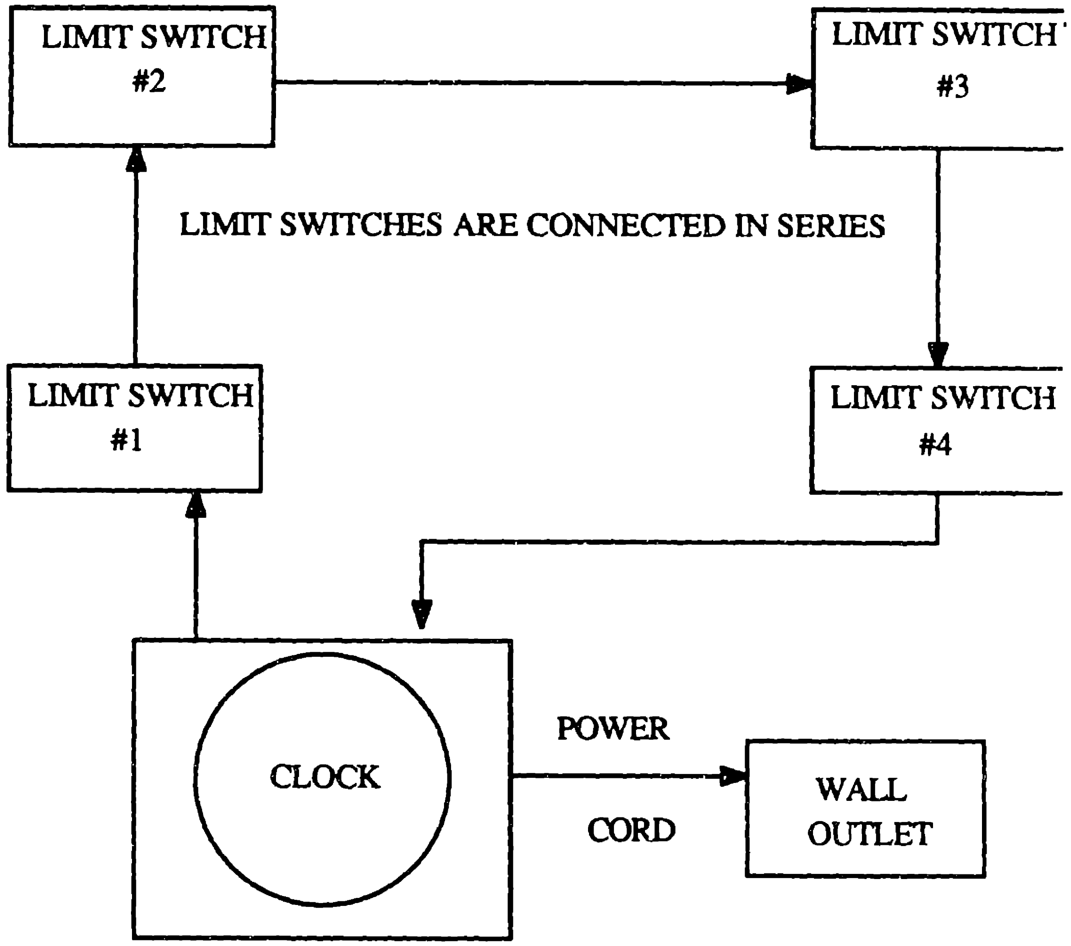

FIGURE 3.9 - TIME RECORDING SYSTEM

CHAPTER 4 - EXPERIMENTAL DESIGN

4.1 TASKS

The tasks consisted of moving the block of wood between four slots (previously described in Chapter 3) with the manipulator arm. Two of the slots were 3.75 inches wide, one was 3.25 inches wide and the fourth was 3 inches wide. These provided three tolerance levels for placing the 2.75 inch wide block between them: one, one half, and one quarter inch tolerances.

The E-2 gripper has a width of 3.75 inches when fully open, issuing a one inch tolerance with which to grasp the block as shown in figure 4.1. This one inch tolerance was then assigned to the largest tolerance for the task board and then halved twice to give the other tolerances. The slots were arranged so that the one inch tolerances were on the far left and far right and the half and quarter inch tolerances were in the middle two slots. Eight inches separated the mid-points of each slot. Thus the distance moved (eight inches) versus the tolerance of fit (1,.5,.25 inches) provided multiples of 2 for easy use of Fitts' law which applies the formula: Index of Difficulty (Id) in bits per task equals $\log_2(2A/B)$, where A equals the distance moved and B equals the tolerance of fit.[1] Fitts' law produces indices of difficulty of 4, 5, and 6 bits per task respectively for the tasks with tolerance levels of 1, .5, and .25 inches.

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[1] Paul M. Fitts, "The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement," Journal of Experimental Psychology, Vol. 47, No. 6, June, 1954, p. 388.

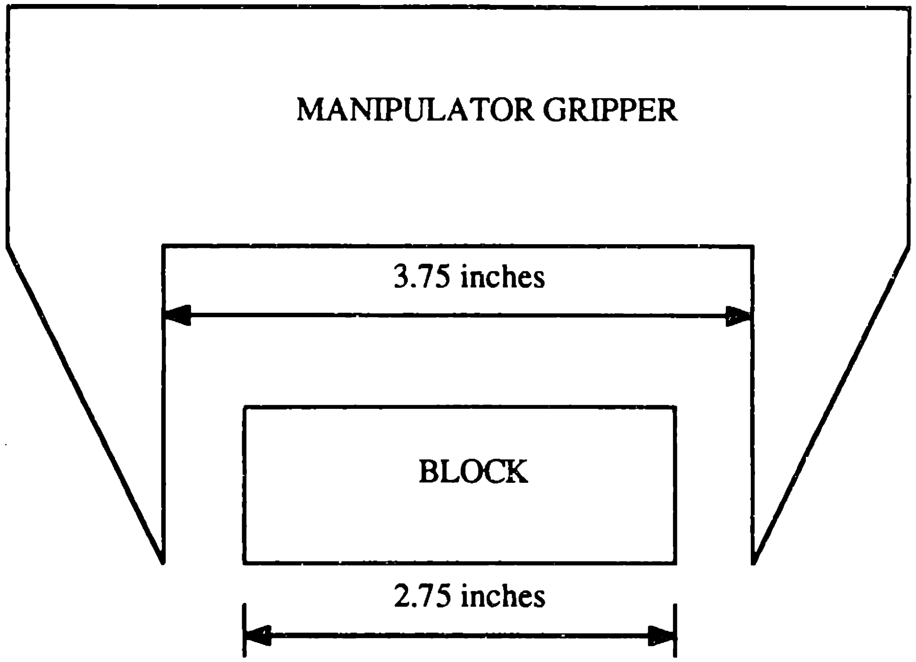

Figure 4.1 - Gripper tolerance.

During the experimental runs, test subjects moved the block between the slots five times going in the right direction and five times going in the left direction for each experimental condition. This provided ten trials per task per experimental condition. The reason for this part of the design was to counterbalance any possible effects of right or left movement, i.e. any possible effects of direction on performance. Not only was the actual movement in a certain direction a concern, but also of interest was whether moving from a larger tolerance to a smaller tolerance or vice-versa could affect the results. This alternating of left and right direction was made possible by the redundancy for the one inch tolerance on the outer slots of the task board.

The tasks were performed with the use of a video monitor and with direct vision under several experimental conditions as described in the following sections.

4.2 USING THE VIDEO MONITOR

Since communication channels for teleoperation in space are often constrained by limited bandwidth for information transmission, decreasing the amount of information that needs to be transmitted can save time and money. Decreasing frame rate is one way to decrease the amount of information that is transmitted, and this section of the experiment was designed to measure the effects of varying frame rate on operator performance. The goal was to gain information on acceptable frame rates for controlling a remote teleoperator under different force feedback and task conditions.

The video monitor was used with three different frame rates: three frames per second (fps), five fps, and thirty fps, with and without force feedback, for a total of six experimental conditions. Thirty frames per second is normal television viewing, and provides satisfactory image fusion. This means that for frame rates higher than thirty fps, the human eye normally cannot tell the differences in transmission of frame rate. (The eye is often thought of as a low pass filter which is why television and movies are customarily shown at frame rates that are no faster than 30 fps.)[2] Therefore 30 fps was selected as the highest frame rate.

Ranadive performed experiments in the MIT Man Machine Systems Laboratory several years ago and found that a threshold frame rate existed at three fps beyond which task performance was virtually impossible.[3] He also discovered that frame rates below 5.6 fps considerably degraded performance and increased variability.[4] Experimentation at the

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[2] Ranadive, Vivek, "Video Resolution, Framerate, and Grayscale Tradeoffs under Limited Bandwidth for Undersea Teleoperation." MIT Masters Thesis, September, 1979, p. 122.

[3] Ranadive, p. 124.

NASA Marshall Space Flight Center measuring performance at 2.5, 5, and 10 fps concluded that at 2.5 fps performance was very poor, but at 5 or 10 fps performance was acceptable. There also was not a significant difference between performance at 5 or 10 fps.[5] Preliminary experimentation confirmed these trends. After trying many frame rates, 30, 5, and 3 fps were chosen since they appeared to mark breaks in the performance curve.

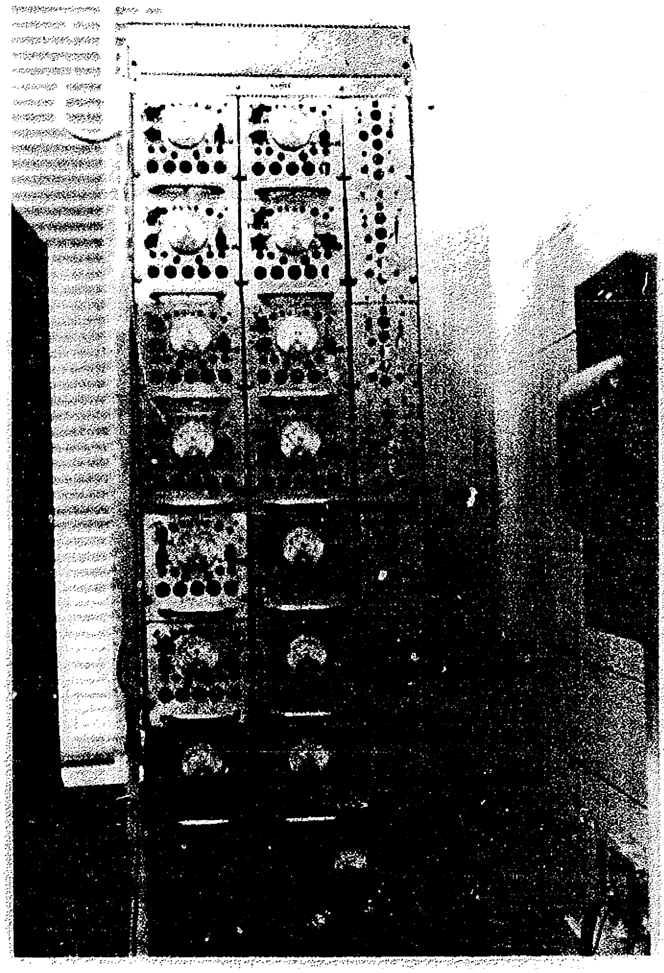

Figure 4.2 - E2 force feedback control panel.

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[4] Ranadive, p. 88.

[5] Joseph Hale, Man/Systems Integration Branch, NASA Marshall Space Flight Center, personal conversation, April 1, 1988.

The tasks were performed for each frame rate both with and without force feedback. The force feedback was turned on and off by adjusting the position and velocity gains providing force feedback information to the human operator. Figure 4.2 shows a photograph of the force feedback control panel for the E2 manipulator.

Since the manipulator arm position had to be moved a total of 24 inches from the leftmost slot to the rightmost slot, reaching the slots and viewing them clearly from a stationary position was found to be a problem during preliminary experimentation. Mobility was necessary in order for the subjects to be able to reach and view each position clearly. The subjects were given the option of standing and being able to move around on their feet, or of sitting on a chair with rollers to provide mobility. All of the subjects opted to perform the task sitting down when using the video monitor since the monitor was only a few feet off of the ground.

The distance between the monitor image and the master manipulator (subject position) was calculated, as was the size of the image of the block, in order to determine the viewing angle for each task. This was important because in order to compare the video environment to the direct viewing environment, a common viewing angle was necessary (see section 4.4). The average size of the block image on the monitor was approximately 1 inch in width and the average viewing distance from the test subject to the monitor was approximately 31 inches. Using the formula: Visual angle = (57.3) L/D, where L = the size of the object and D = the distance from the front of the eye to the object yields a viewing angle of 1.64 degrees.[6] A photograph of the author interacting with the video viewing environment is displayed in figure 4.3

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[6] Robert W. Bailey, Human Performance Engineering: A Guide For System Designers (Englewood Cliffs: Prentice-Hall, Inc., 1982), p. 55.

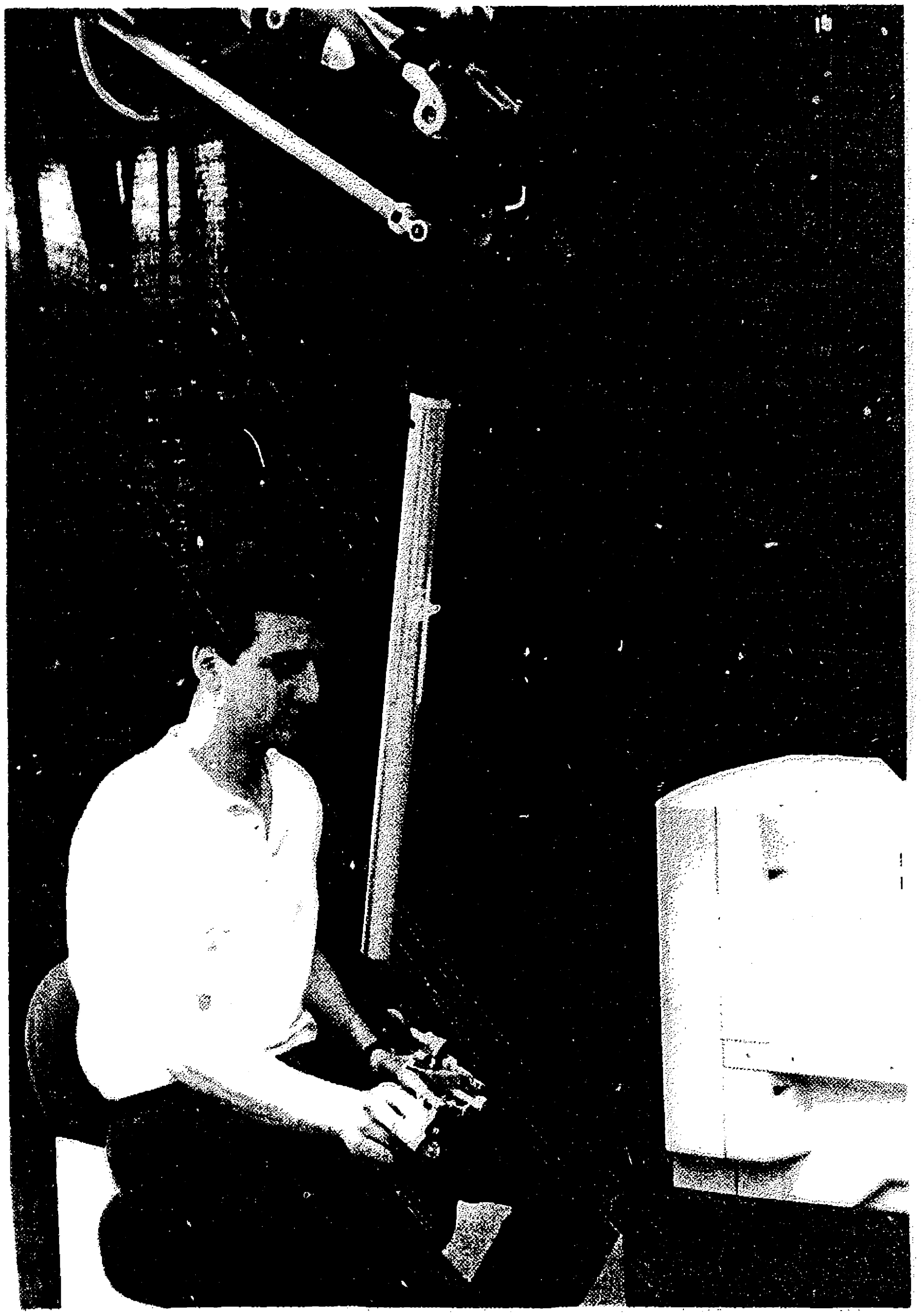

Figure 4.3 - Author pictured in the video viewing environment.

A black cloth was placed in front of the subject to block the direct view of task board making the subject totally dependent on the video monitor for visual feedback. The camera was placed in front of the cloth and was slightly to the left of the center of the task board. After preliminary experimentation this position was selected to provide a good perspective, not obstruct the view by having the slave arm get in the way, and provide an equally good view of each slot.

4.3 USING DIRECT VISION

The tasks were also performed with the subjects using direct vision for visual feedback, with and without force feedback. The master manipulator was placed at three different viewing distances from the task board: four, eight, and twelve feet. These viewing distances along with the block image being its actual 2.75 inches in width provided viewing angles of 3.28 degrees, 1.64 degrees, and 1.09 degrees respectively. This allowed analysis of the effects of varying distances and viewing angles on task times.

The subjects were allowed to either sit on a rolling chair or stand to provide mobility in using the manipulator arm, and to allow for a clear view of the task being performed. The three different positions with and without force feedback gave six experimental conditions for direct viewing. A photograph of the author in the direct viewing environment is shown if figure 4.4.

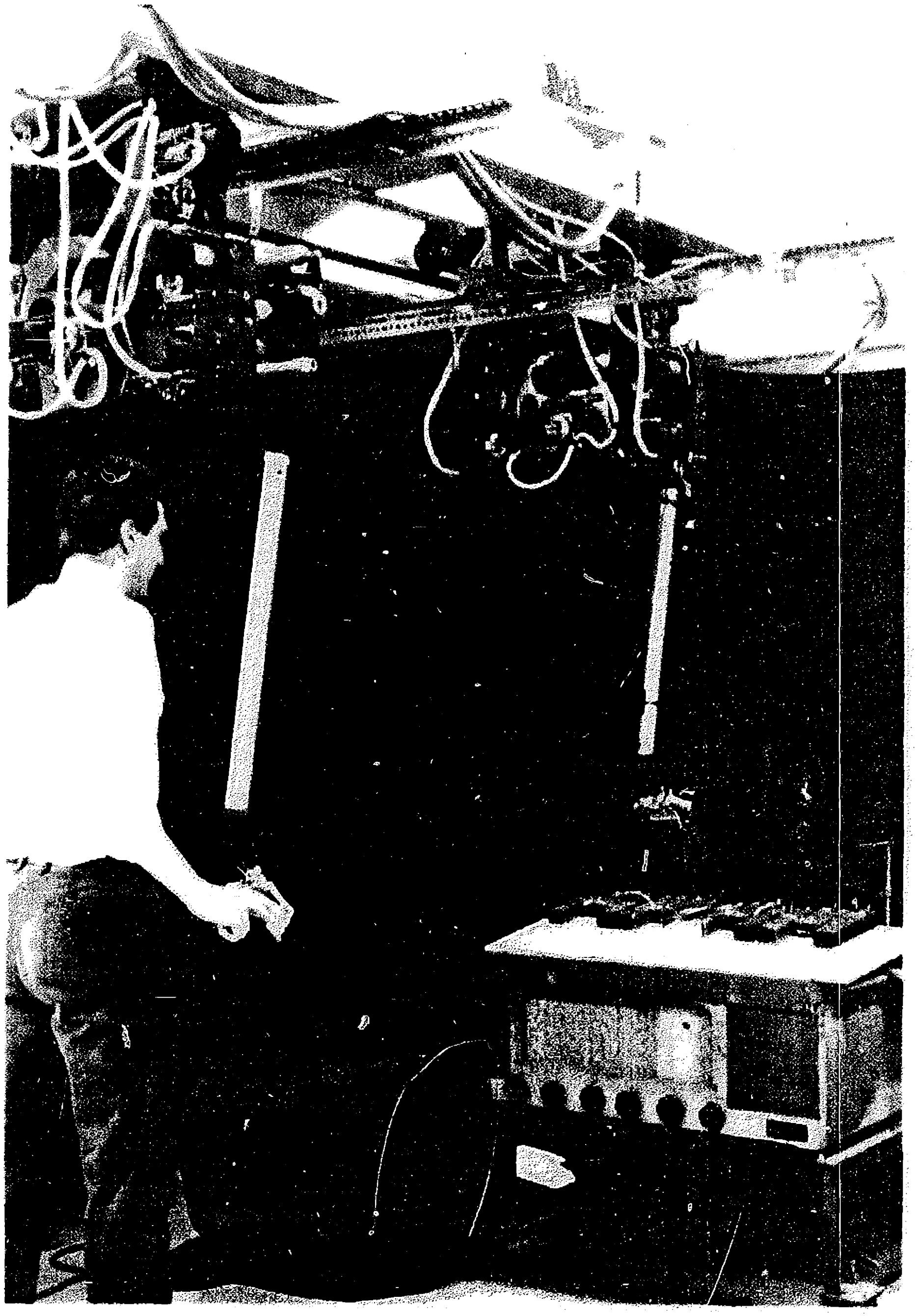

Figure 4.4 - Author pictured in direct viewing environment.

4.4 DIRECT VIEWING AT 8 FEET AND VIDEO VIEWING AT 30 FPS

The eight foot distance yields the same viewing angle as the experiments that were performed with the video monitor (1.64 degrees). This allows for a comparison of the eight foot direct viewing data with the 30 fps video data since, as mentioned earlier, 30 fps appears to the eye as a steady motion. Thus eight foot direct data and 30 fps video data had viewing angles and frame rates that appeared equal to the human operator. The only major differences were stereo vision with direct viewing, the ability to move one's head to change the viewing line of sight with direct viewing, and the different environments surrounding the task board for each view. It was the effects on performance of the stereo vision and other differences in the views that were of interest in this section of the experimental design.

4.5 EXPERIMENTAL PROCEDURES

Six subjects were used. Each subject was brought into the Man/Machine Systems Laboratory for a training session, and then two separate experimental sessions: one using the video monitor and the other for performing the tasks with direct vision. Three subjects used direct vision first and three used the video monitor first. The subject numbers and scheduling of sessions were assigned on a random basis. For each session a subject performed the tasks under six separate conditions as described in sections 4.2 and 4.3. The ordering of the conditions was allocated using a balanced latin square method to counterbalance for learning and fatigue. The balanced latin square insures that each condition precedes and follows each other condition the same number of times. Each condition for each session was randomly assigned a number as follows:

Direct Vision:

1) 12 ft, force feedback
2) 12 ft, no force feedback
3) 8 ft, no force feedback
4) 4 ft, no force feedback
5) 4 ft, force feedback
6) 8 ft, force feedback

Video Monitor:

1) 30 fps, force feedback
2) 5 fps, force feedback
3) 3 fps, force feedback
4) 3fps, no force feedback
5) 5 fps, no force feedback
6) 30 fps, no force feedback

The balanced latin square technique yielded the following ordering assignments for each subject:

Subj. #1	Subj. #2	Subj. #3	Subj. #4	Subj. #5	Subj. #6
1	2	3	4	5	6
2	3	4	5	6	1
6	1	2	3	4	5
3	4	5	6	1	2
5	6	1	2	3	4
4	5	6	1	2	3

Since each task was performed an equal number of times going to the left and an equal number of times going to the right, effects due to direction were also analyzed.

The video portion consisted of three frame rates (30, 5, and 3 fps), two forms of force feedback (with and without), and three different tolerances (1, .5, and .25 inches) or three different indices of difficulty (4, 5, and 6 bits/task) for a 3x2x3 design (see figure 4.5). The direct vision experiments included three viewing distances (4, 8, and 12 feet), and the previously stated feedback and tolerance parameters for a 3X2X3 design (see figure 4.6). Each task was performed five times going to the right and five times going to the left for 5X2 = 10 tasks per condition. Six subjects were used so the video experiments had a total of 3x2x3x5x2x6 = 1080 number of data points, and the direct vision experiments also yielded a total of 3x2x3x5x2x6 = 1080 number of data points.

Task times were recorded by using the time recording system described in section 3.4. The task would begin with the block in a slot and the clock reading zero. The experimenter would indicate to the subject with a hand signal to begin the task and whenever the subject was ready. The subject would grasp the block and remove it from the slot, and insert it in the proper slot. Task time was recorded, the clock reset by the experimenter, and the next task would proceed in the same manner.

During preliminary experimentation and subject training it was noticed that sound feedback from the limit switch being depressed, the clock starting and stopping, and the block making contact with the task board and slots was aiding the operator. Sound feedback played a larger role when the visual and motor senses were degraded by decreasing frame rate, or no force feedback. To nullify the effects of sound feedback each subject wore ear plugs and stereo headphones to mask out any sound feedback.

If a subject lost hold of the block while performing a task and the block fell from the gripper, the block was placed in the previous slot and the clock was reset. The subject was also allowed to change a grip on the block before performing a task to ensure that the block would be grasped properly. This allowed for the task time to reflect the time of movement of the block under the various conditions in addition to the common grasping time.

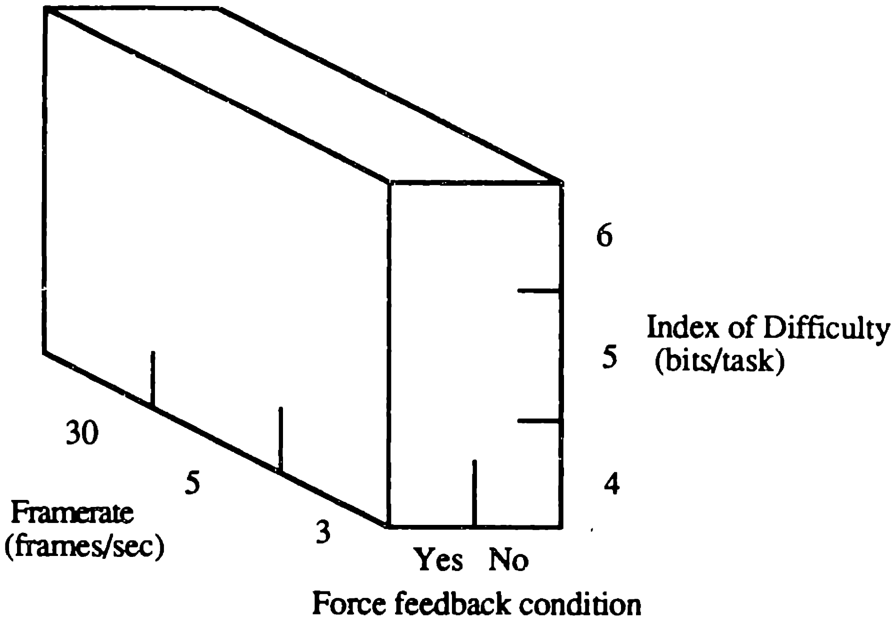

Figure 4.5 - Video viewing experimental design

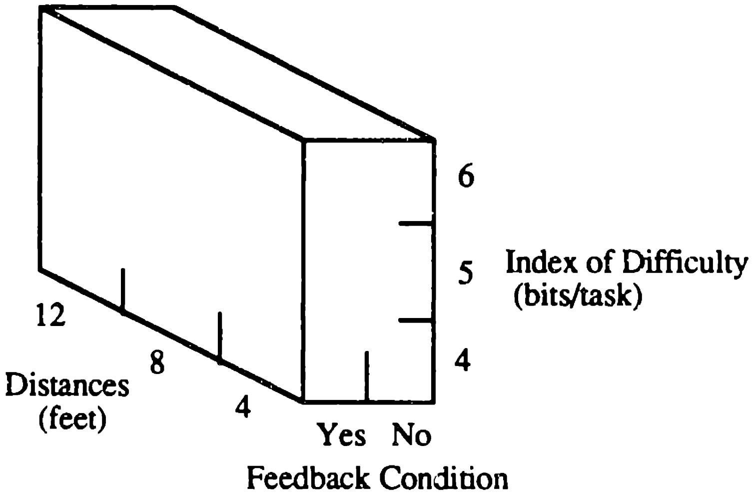

Figure 4.6 - Direct viewing experimental design.

4.6 TEST SUBJECTS AND TRAINING

Each subject attended a one and a half to two hour training session a few days prior to performing the final experimentation runs. The subjects were made familiar with the experimental design and procedures and became acquainted with the manipulator system in the Man/Machine Systems Laboratory. They performed each task condition and repeated the tasks until they said they were familiar and felt comfortable with the manipulator and the manipulation environment. Then they performed the tasks for time just as they would in the actual experiments. When their performance times met minimum training levels and the learning effects subsided, the subjects were then trained on the next experimental condition.

Subjects were brought in for two separate experimental sessions: one using direct vision and one using the video as described earlier. Each of these sessions lasted from one to two hours. Before the training and experimental sessions the subjects were required to read the information on the following page.

Subject Instructions
M. Massimino Thesis Experiments
Man/Machine Systems Laboratory

You will be using the remote manipulator system to perform tasks involving placing a block in three different sized slots. You are to perform each task as quickly as possible, but you must be sure at the end of each task that the block is completely in the slot making contact with the switch at the back of the slot. Your task time will be recorded by the experimenter. The clock will automatically begin running when the block is removed from a slot and contact is broken with the switch. The clock will automatically stop running when the block makes contact with the switch in the next slot. You should continue with the task until you are sure that you have made contact with the switch, and then inform the experimenter that you are done. You should begin a task when the experimenter gives you a signal to begin and you are ready to attempt the next task. If you drop the block at any time during the task, notify the experimenter of the drop and the task will be redone. You will be wearing ear plugs and headphones to cut off any possible sound feedback. If at any time you feel any discomfort or constraint with the headphones, manipulator arm, the manipulator gripper, or anything else please notify the experimenter immediately.

You will be required to attend three separate sessions (sessions 2 & 3 not necessarily in this order):

1) A one to two hour training session to become familiar and proficient with the equipment and experimental methods.

2) A one to two hour session where you will perform the tasks using direct vision. Tasks will be performed with and without force feedback, and with the manipulator arm at three different distances from the task board.

3) A one to two hour session where you will perform the tasks using a video monitor for visual feedback with three different frame rates. The tasks will be performed with and without force feedback, and with the manipulator at a single distance from the task board.

For sessions 2 and 3, performing tasks under the different conditions will be done in a random order for each subject.

CHAPTER 5 - EXPERIMENTAL RESULTS

5.1 EXPERIMENTAL DATA AND STATISTICAL METHODOLOGIES

Appendix B contains the experimental results for each subject individually, and the average task times over all subjects combined. These results were analyzed through the statistical analysis tools described in Appendix A. This chapter applies the statistical methodologies outlined in Appendix A to the experimental data presented in Appendix B.

5.2 VIDEO VIEWING PERFORMANCE RESULTS

5.2.1 EFFECTS OF FRAME RATE

Table 5.1 shows that frame rate produced an F value of 73.1 with two degrees of freedom (d.f.) for the frame rate variable and two times five (2 d.f. for frame rate and 5 d.f. for subject) or ten degrees of freedom for the frame rate error term. This can be abbreviated as F(2,10) = 73.1. An associated level of significance was calculated at 0.0001, or abbreviated as $p < .0001$. This represents a very high likelihood that variable frame rates of three, five, and thirty frames per second did cause significant differences in performance times. Information on ANOVA is presented in Appendix A.

The Newman-Keuls post-hoc test (table 5.2) showed that all three frame rates were significantly different. Information on the Newman-Keuls procedure is located in Appendix A.

Table 5.1 - ANOVA Results for Video Viewing Performance Results for Variables and Interactions Having Significant Differences

SOURCE	DF	SS	MS	F-VALUE	P-VALUE
Frame rate	2	147	73.6	73.1	0.0001
Error	10	10.1	1.01		
Force Feedback	1	145	145	167	0.0001
Error	5	4.35	0.871		
Index of Difficulty or Tolerance Level	2	34.6	17.3	15.3	0.0009
Error	10	11.3	1.13		
Frame rate*Force Feedback	2	22.8	11.4	8.99	0.0058
Error	10	12.7	1.27		

DF = degrees of freedom, SS = sum of squares, MS = mean square

Table 5.2 - Post-Hoc Test Results for Frame rate

alpha = 0.05, degrees of freedom = 10, mean square error = 10.1

r-value	2	3
critical range	0.527	0.648

All three means are statistically significant.

FRAME RATE (FPS)	MEAN (SEC.)	STD. ERROR	N	GROUPING
3	5.36	0.165	360	A
5	4.48	0.139	360	B
30	2.56	0.0662	360	C

Mean task time with a frame rate of five frames per second (fps) was an average of seventy-five percent (1.92 seconds) longer than at the thirty fps frame rate. This increase in time was due to an approximately eighty-three percent decrease in frame rate. Going from five frames per second to three frames per second represents a forty percent decrease in frame rate and had an associated twenty percent (.88 seconds) increase in time. Changing frame rate from thirty to three is a ninety percent decrease in frame rate and the time increase was one hundred and nine percent (2.8 seconds). As expected decreasing frame rate does increase performance times. At three frames per second performance time was drastically increased, since the extra seven percent decrease in frame rate from 30 to 3 as opposed to 30 to 5 produced an extra 34 percent increase in time.

These results are displayed in figure 5.1 which plots mean task time versus frame rate, with the error bars representing the standard error of the mean. The regression curve that best fit the data was a logarithmic plot yielding task time (y) and frame rate (x) related by y=7.55*x^-0.318, with an R-value of 1.00. The R-value measures how well the regression fit the data, with R=1 as the best possible case. This logarithmic plot reinforces the observed trends in the increasing rate of mean task times at lower frame rates. These results are also in agreement with what Ranadive concluded: at lower frame rates, task times begin to increase drastically when compared to similar incremental changes at higher frame rates.[1] The observed results lead one to conclude that decreasing frame rate will increase performance times gradually as frame rate is gradually decreased from thirty frames per second. However, decreasing frame rate will increase performance times at an even greater rate in the regions surrounding five fps to three fps. There may also be, as

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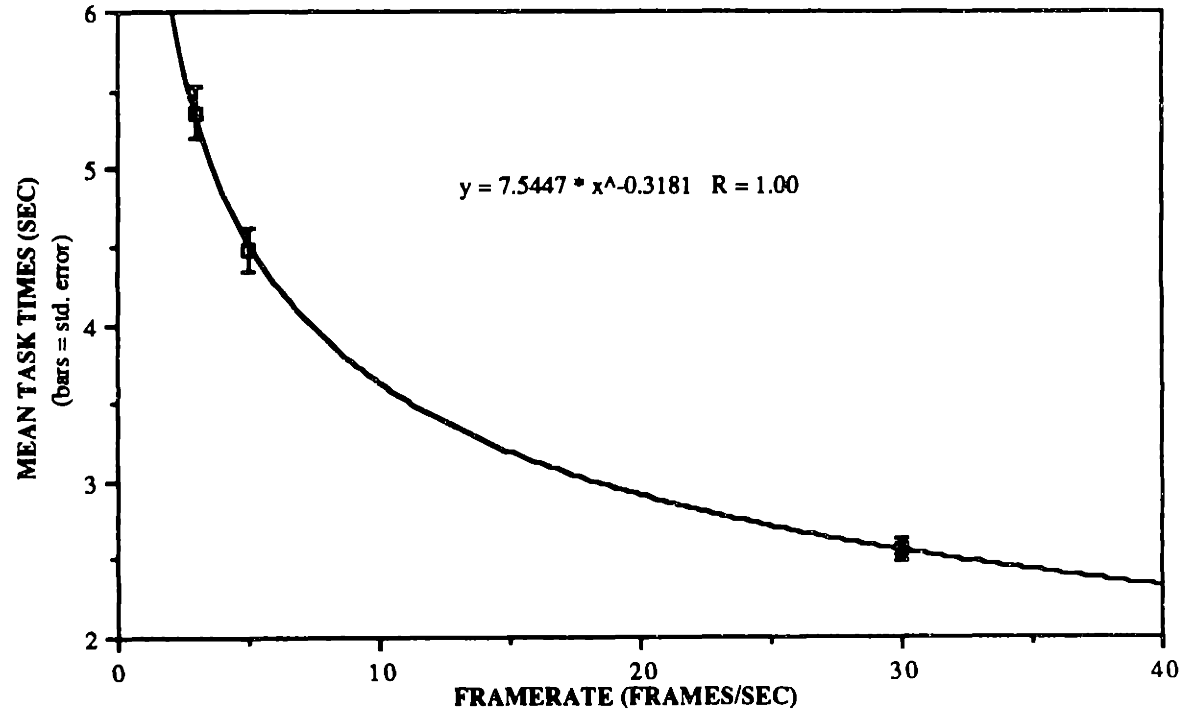
[1] Vivek Ranadive, "Video Resolution, Frame Rate and Grayscale Tradeoffs Under Limited Bandwidth for Undersea Teleoperation," MIT Masters Thesis, September, 1979, p. 88.

Ranadive observed a certain threshold or cut-off frame rate at which performance time will drastically increase or at which acceptable performance would be impossible.[2]

FIGURE 5.1 - FRAMERATE EFFECTS ON VIDEO VIEWING PERFORMANCE



Although these results are based on only three data points, each data point is the mean of three hundred and sixty data observations. Therefore it is with some confidence that these results and interpretations are presented.

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[2] Ranadive, p. 124

5.2.2 EFFECTS OF FORCE FEEDBACK

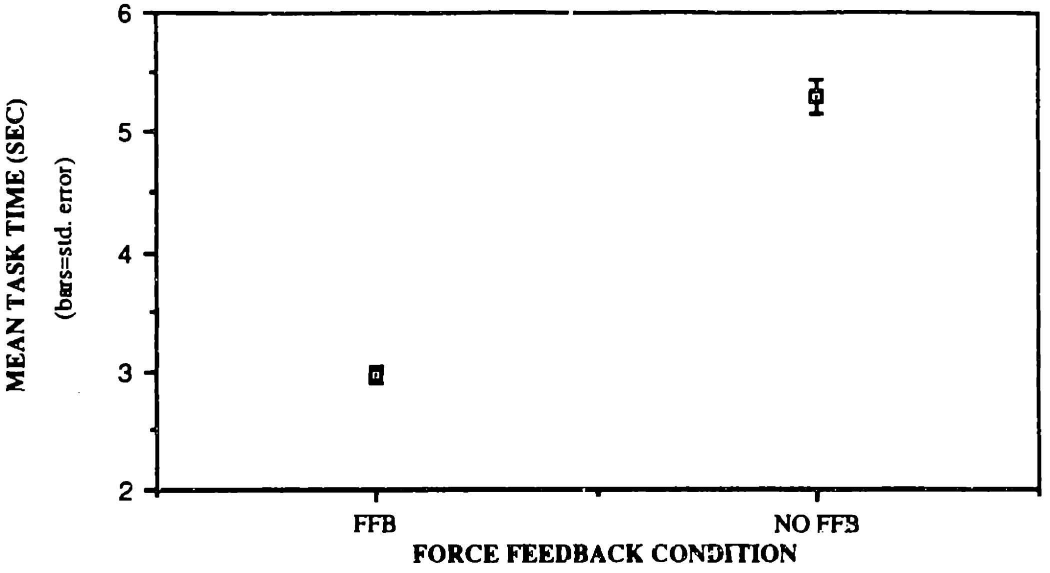
Table 5.3 - Results for Force Feedback

Both means are statistically significant.

FORCE FDBK CONDITION	MEAN (SEC.)	STD. ERROR	GROUPING
FORCE FEEDBACK	2.98	0.0629	A
NO FORCE FEEDBACK	5.29	0.137	B

Force feedback also made a significant difference in performance, $F(1,5) = 167$, $p < 0.0001$ (table 5.1). Table 5.3 shows that with force feedback the average task time for all frame rates combined was 2.98 seconds and the absence of force feedback produced a combined average task time of 5.29 seconds. Thus performing the tasks without force feedback yielded a seventy-eight percent increase in performance times. These results are shown graphically in figure 5.2.

FIG. 5.2 - FORCE FEEDBACK EFFECTS ON VIDEO VIEWING PERFORMANCE



Hill and Salisbury also found in their experiments that with force feedback task completion times were significantly shorter than without force feedback for peg-in-hole tasks.[3] Further, Hill concluded that difficult tasks such as crank and turn operations were done twice as fast when force feedback was present.[4] He also found that force feedback was more important for some motions such as fitting, but not as important for other motions such as positioning. Results such as these have led to the design of force reflecting hand controllers and the control of manipulation through kinesthetic coupling to provide the operator with a more physical sense of what he/she is actually doing during the manipulation task.[5]

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[3] J.W. Hill and J.K. Salisbury, "Study to Design and Develop Remote Manipulator Systems," Annual Report, NASA Contract NAS2-8652, Nov., 1977, p.38.

[4] J.W. Hill, "Study of Modeling and Evaluation of Remote Manipulation Tasks with Force Feedback," Final Report, JPL Contract 95-5170, March, 1979, p. 24.

[5] A.K. Bejczy and J.K. Salisbury, Jr., "Controlling Remote Manipulators Through Kinesthetic Coupling," Computers in Mechanical Engineering, July, 1983, p. 48.

5.2.3 EFFECTS OF TASK DIFFICULTY

Table 5.1 displays that task difficulty did make a significant difference F(2,10) = 15.3, $p < 0.0009$. The Newman-Keuls data displayed in table 5.4 shows that only the quarter inch tolerance or the most difficult task (Id=6 bits) has significantly different mean task times from the other two tasks. The one inch tolerance task with Id=4 and the half inch tolerance task with Id=5 were not significantly different from each other. This can be further explained by looking at the task time means for each index of difficulty. The task with the half inch tolerance and Id=5 had only an 11 percent (.40 seconds) increase in mean task times when compared with the Id=4 task. But the Id=6 task had 24 percent (.95 seconds) and 38 percent (1.35 seconds) increases in average task times when compared with the Id=5 and Id=4 tasks respectively.

Table 5.4 - Post-Hoc Test Results for Task Difficulty

alpha = 0.05, degrees of freedom = 10, mean square error = 11.3

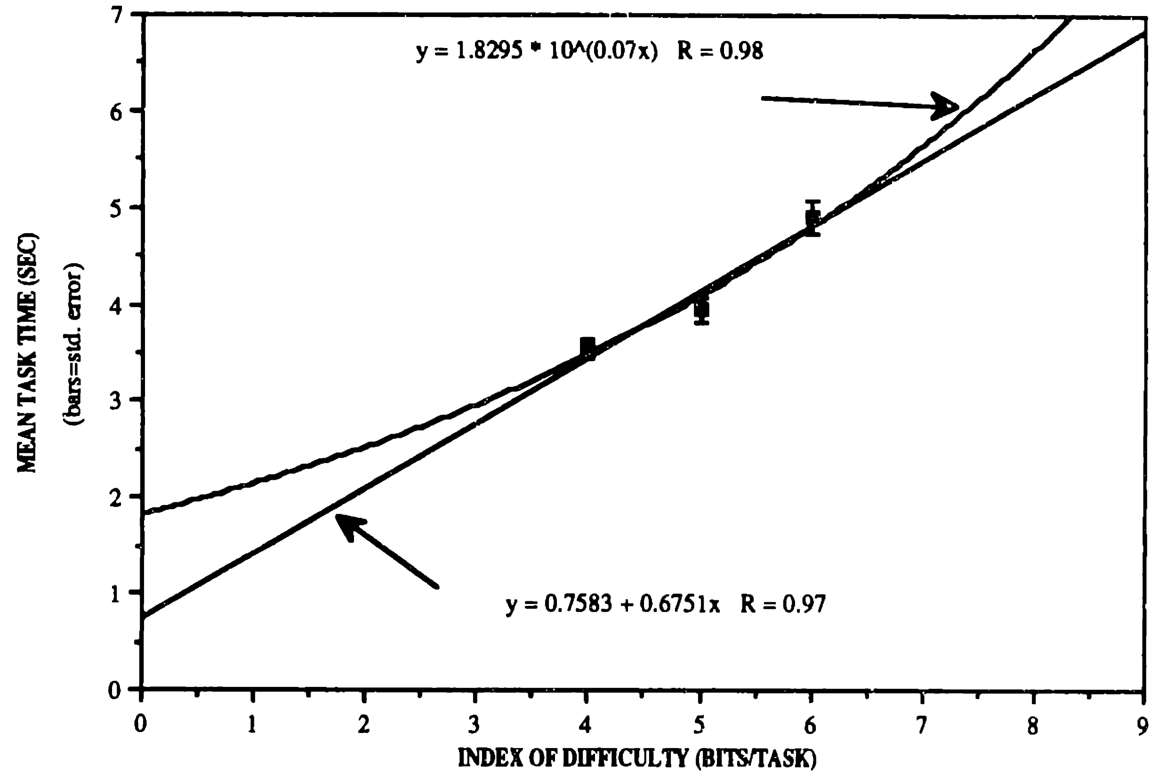
r-value	2	3
critical range	0.559	0.687

Means with the same letter for grouping are not statistically significant.

INDEX OF DIFF.	TOLERANCE	MEAN (SEC.)	STD. ERROR	N	GROUP
6 bits/task	.25 inches	4.90	0.178	360	A
5 bits/task	.5 inches	3.95	0.128	360	B
4 bits/task	1.0 inch	3.55	0.109	360	B

Fitts hypothesized that task times have an increasing linear relationship with increasing task difficulty.[6] His findings were reenforced by the experiments that McGovern conducted. McGovern found that Fitts' index of difficulty was fairly accurate and useful in modeling human performance for the use of remote manipulators.[7]

FIG. 5.3 - TASK DIFF. EFFECTS ON VIDEO VIEWING PERFORMANCE



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[6] Paul M. Fitts, "The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement," The Journal of Experimental Psychology, Vol. 47, No. 6, June, 1954, pp. 381-391.

[7] Douglas Edward McGovern, "Factors Affecting Control Allocation for Augmented Remote Manipulation," Ph.D. Thesis, Design Division, Mechanical Engineering Department, Stanford University, Stanford, California, November, 1974, p. 203.

Task times increased at a faster rate going from Id=5 to Id=6 than when increasing difficulty from Id=4 to Id=5. These relationships are more clearly represented in figure 5.3. The mean task time values are plotted for the three different indices of difficulty. The error bars represent the standard error for each mean. A linear regression yielded $y=0.758+ 0.675x$, with an R-value of 0.97. An exponential fit was also done, yielding a relationship of time (y) to index of difficulty (x) of $y=1.83*10^{\wedge}(0.07x)$ with an R-value of 0.98. By looking at the two fitted lines, examining the pattern of the data points, comparing R-values, and considering the results of the Newman-Keuls post-hoc test, one can conclude that the exponential plot describes the behavior of the data better than the linear plot. This is a different result than what Fitts obtained, but is similar to the results of Hill.[8]

5.2.4 EFFECTS OF DIRECTION

Half of the data points for each task were recorded with the block being moved from left to right, with the other half being recorded with the block being moved right to left. The ANOVA results for direction effects with video viewing were $F(1,5) = .00398$, $p > .05$, indicating that direction did not make a significant difference. These F and p-values were not calculated by the SAS program, but were instead calculated by hand.[9] The means were nearly identical. The mean for right to left movement for all conditions was 4.13 seconds and for left to right movement the mean was 4.14 seconds. Not all combinations of going to and from every tolerance level with every direction were tested. However for

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[8] J. W. Hill, "Two Measures of Performance in a Peg-in-Hole Manipulation Task with Force Feedback," in MIT Proceedings, 13th Annual Conference on Manual Control, June 15-17, 1977, p. 304.

[9] Francis J. Wall, Statistical Data Analysis Handbook (New York: McGraw-Hill, 1986), pp. 16.1-16.8.

the combinations that were tested, coming out of a smaller or larger tolerance level did not make a significant difference in task performance times.

5.2.5 INTERACTION EFFECTS OF FRAME RATE WITH FORCE FEEDBACK

The interaction of frame rate and force feedback was also noticed to make a significant difference in performance times, F(2,10) = 8.99, $p < .006$ as displayed in table 5.1. This interaction effect was studied further with the Newman-Keuls post-hoc tests and the results are displayed in table 5.5.

Three frames per second (fps) with force feedback, five fps with force feedback, and thirty fps without force feedback were found to produce mean task times that were not significantly different. Three fps without force feedback and five fps without force feedback were not significantly different. Thirty fps with force feedback was significantly different from all other conditions.

At each frame rate, force feedback made a significant improvement in performance times. Thirty fps made a significant difference over the other two frame rates both with and without force feedback. Further, force feedback yielded a larger performance improvement at lower frame rates than at higher frame rates. Even at 3 fps, force feedback provided such a large improvement in performance that the mean task time was not significantly different from 30 fps without force feedback. These results indicated that force feedback can improve performance and make up for the negative effects of a low frame rate. Conversely without force feedback, a higher frame rate can also improve performance and can balance out some of the negative effects of not having force feedback.

Table 5.5 - Post-Hoc Test Results for Interaction of Frame rate and Force Feedback

alpha = 0.05, degrees of freedom = 10, mean square error = 12.7

r-value	2	3	4
critical range	0.838	1.03	1.15

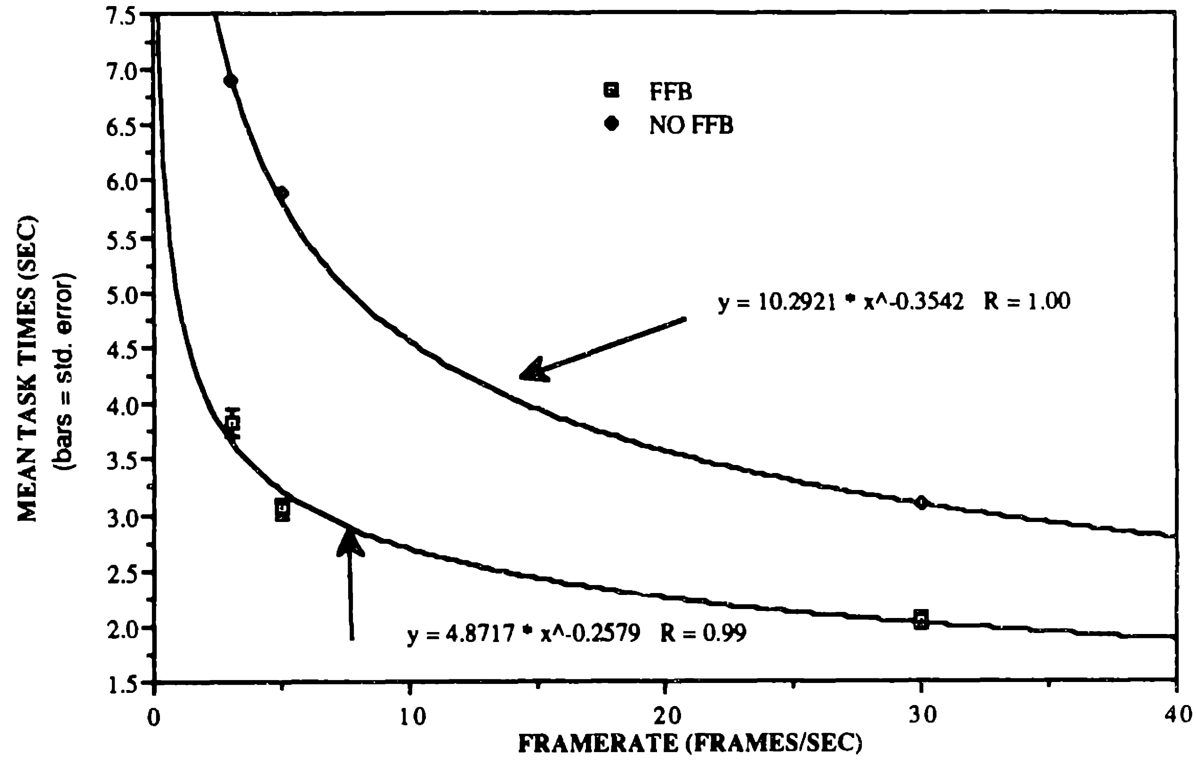
Means with the same letter for grouping are not statistically significant.

FFB	FR (FPS)	MEAN (SEC.)	STD. ERR.	N	GROUP
YES	3	3.82	0.124	180	A
NO	3	6.90	0.259	180	B
YES	5	3.06	0.0827	180	A
NO	5	5.90	0.220	180	B
YES	30	2.05	0.0690	180	C
NO	30	3.08	0.0994	180	A

FFB = Force feedback condition, FR = frame rate, N = number of observations

Looking at each curve individually in figure 5.4 provides some additional information. The curve fit that best describes the data for frame rate with force feedback is a logarithmic fit with y=4.87*x^-0.256, R=0.99. A similar trend was calculated for the task means without force feedback, a logarithmic fit, y=10.3*x^-0.354, R=1.00. The curves reflect the same trends for task time and frame rate that were discussed in section 5.2.1

FIG. 5.4 - INTERACTION OF FRAMERATE AND FORCE FEEDBACK



5.3 DIRECT VIEWING RESULTS

5.3.1 EFFECTS OF VIEWING DISTANCE

Table 5.6 - Analysis of Variance Results for Variables and Interactions With Statistical Significance for Direct Viewing Performance

SOURCE	DF	SUM OF SQ.	MEAN SQ.	F-VALUE	P-VALUE
VIEWING ANGLE OR DISTANCE	2	8.14	4.07	57.8	0.0001
ERROR	10	0.704	0.070		
FORCE FEEDBACK	1	32.0	32.0	49.5	0.0009
ERROR	5	3.23	0.646		
INDEX OF DIFFICULTY OR TOLERANCE	2	13.6	6.79	27.3	0.0001
ERROR	10	2.48	0.248		
DISTANCE & FORCE FEEDBACK INTERACTION	2	2.06	1.03	6.91	0.013
ERROR	10	1.49	0.149		

Table 5.6 shows that distance did cause significant differences in mean task times, F(2,10) = 57.8, $p < .0001$. The Newman-Keuls post-hoc analysis determined that all the distances produced task time means that were significantly different from each other (see table 5.7).

Table 5.7 - Post-Hoc Test Results for Distance/Viewing angle

alpha = 0.05, degrees of freedom = 10, mean square error = 0.704

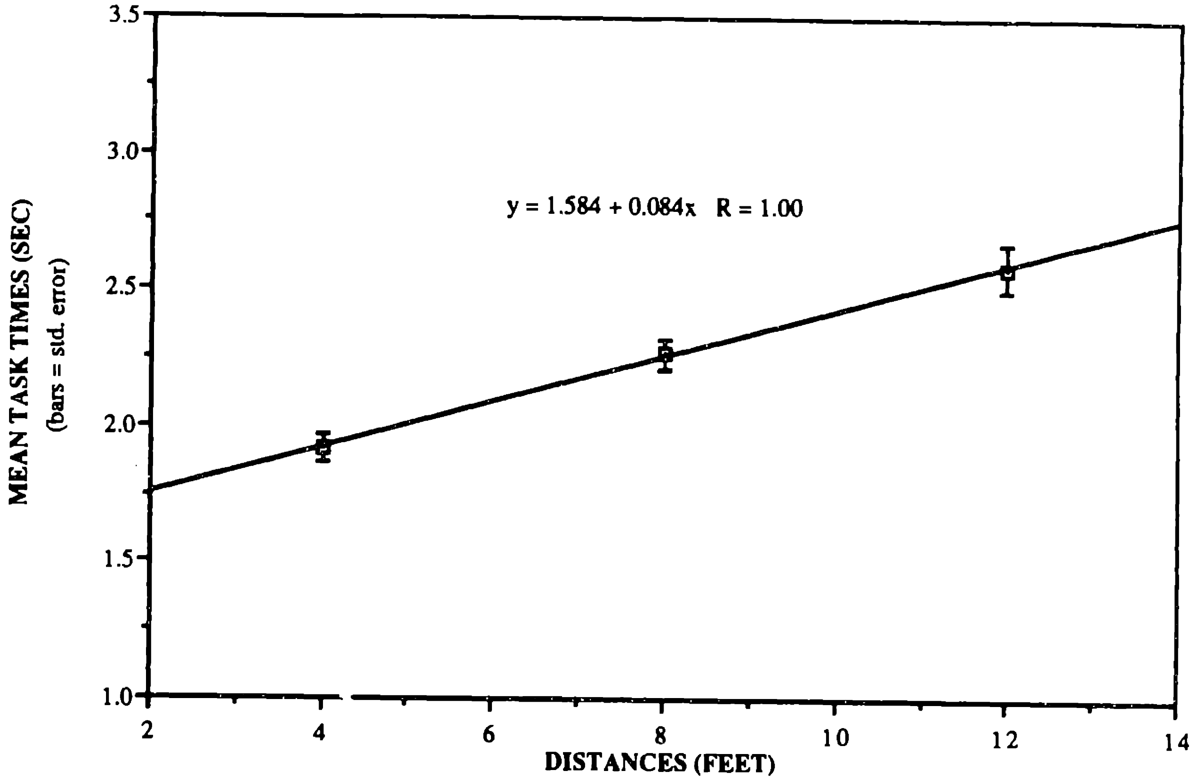
r-value	2	3
critical range	0.139	0.171

All three means are statistically significant.

DIST. (FT)	VIEW. ANGLE	MEAN (SEC.)	STD. ERR.	N	GROUPING
12	1.09 Degrees	2.59	0.0816	360	A
8	1.64 Degrees	2.27	0.0573	360	B
4	3.28 Degrees	1.92	0.0527	360	C

The post-hoc tests reveal that there was a fairly uniform increase in performance times as the distance from the task board was increased. Increasing the distance from four feet to eight feet, a one hundred percent increase, increased performance time by 18 percent (.35 seconds). Going from four feet to twelve feet, a two hundred percent increase in distance, yielded an 35 percent (.67 seconds) increase in task time. Thus the first extra four feet from the closest point yielded a .35 second increase in task time, and the second extra four feet produced a .32 second increase in task time. Figure 5.5 displays this linear relationship graphically. The line $y=1.58+0.084x$, $R=1.00$ is linear and fits the data well.

FIGURE 5.5 - DISTANCE EFFECTS ON DIRECT VIEWING PERFORMANCE



5.3.2 EFFECTS OF VIEWING ANGLE

Each distance from the task board has an associated viewing angle. The formula: viewing angle = (57.3) (60) L/D degrees, gives a measure for viewing angle where L = the size of the object measured perpendicular to the line of sight, and D = the distance from the front of the eye to the object.[1] In this case L = 2.75 inches and D varied between 4 feet (48 inches), 8 feet (96 inches), and 12 feet (144 inches), yielding viewing angles of 3.28 degrees, 1.64 degrees, and 1.09 degrees respectively. The analysis of variance and

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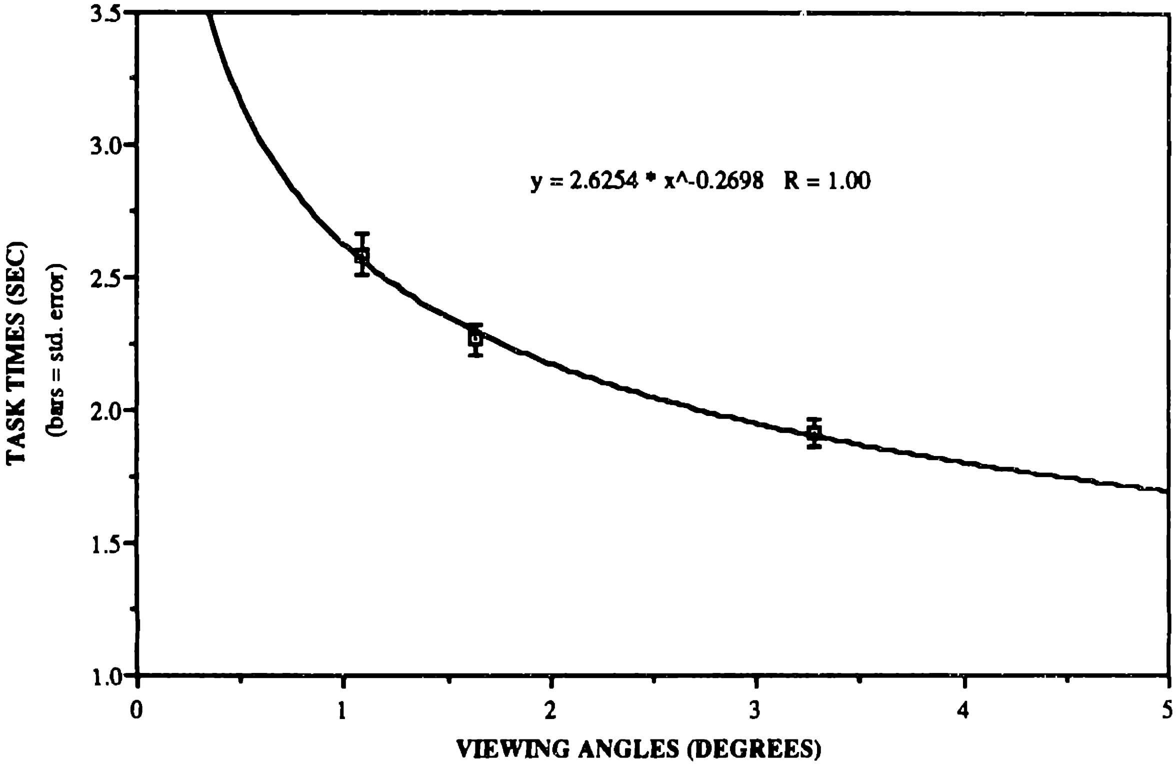
[1] Robert W. Bailey, Human Performance Engineering: A Guide for System Designers, (Englewood Cliffs: Prentice Hall, Inc., 1982), pp. 55-56.

Newman-Keuls results for viewing angle are the same as those for distance in tables 5.6 and 5.7.

Mean task time does not change with viewing angle the same as with distance. This is because viewing angle does not increase linearly as distance does (4 to 8 to 12 feet), but rather it decreases more rapidly initially, 3.28 to 1.64, then more slowly, 1.64 to 1.09 degrees. Because of this, the mean task times plotted against viewing angle did not behave linearly but rather they behaved logarithmically, y=2.63*x^-0.270, R=1.00 as displayed in figure 5.6.

FIG. 5.6 - VIEWING ANGLE EFFECTS ON DIRECT VIEWING PERFORMANCE



5.3.3 FORCE FEEDBACK EFFECTS ON DIRECT VIEWING PERFORMANCE

As table 5.6 indicates, force feedback also made a significant difference in the mean task times for direct viewing performance F(1,5) = 49.5, p < .0009. The presence of force feedback yielded a total mean task time of 1.71 seconds and task times without force feedback had a total mean task time of 2.80 seconds (see table 5.8).

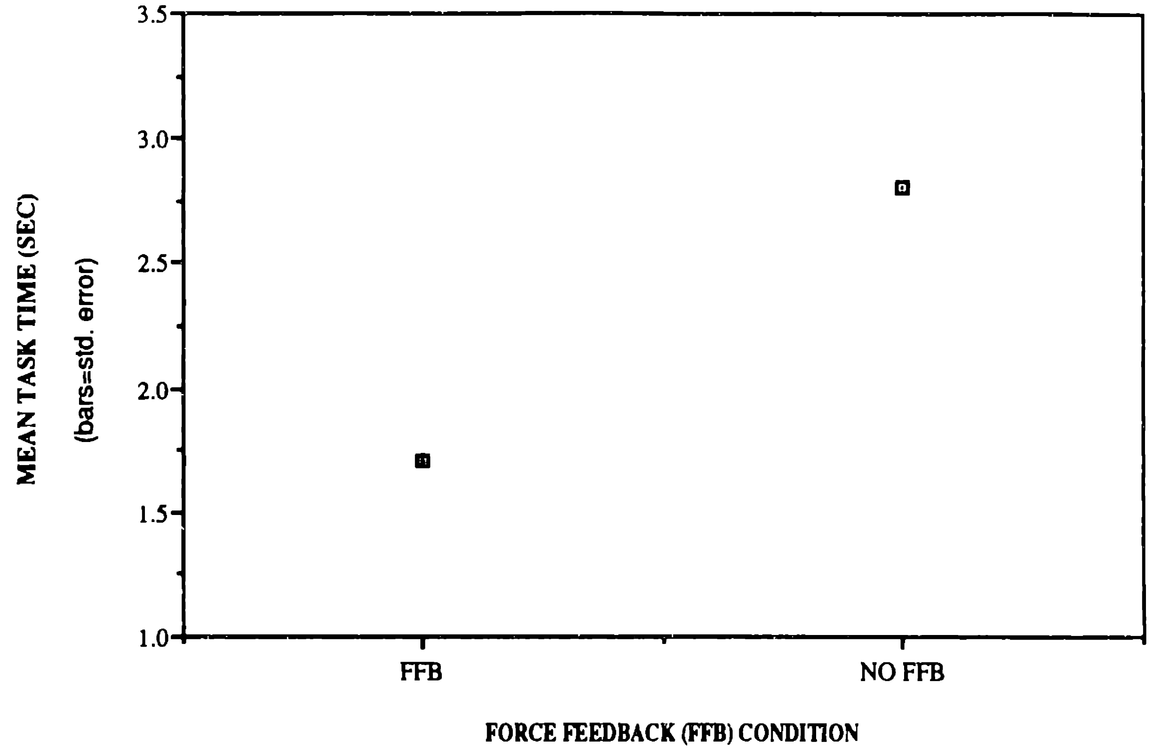
Table 5.8 - Results for Force Feedback.

Both means are statistically significant

FORCE FDBK CONDITION	MEAN (SEC.)	STD. ERROR	GROUPING
FORCE FEEDBACK	1.71	0.0279	A
NO FORCE FEEDBACK	2.80	0.0636	B

Therefore force feedback produced a 39 percent (1.09 seconds) improvement in operator performance for direct viewing. These results are shown graphically in figure 5.7 where the mean task times are plotted against the feedback conditions.

FIG. 5.7-FORCE FEEDBACK EFFECTS ON DIRECT VIEWING PERF.



5.3.4 TASK DIFFICULTY EFFECTS ON DIRECT VIEWING PERFORMANCE

Tolerance level, or task difficulty, made a significant difference in performance, F(2,10) = 27.3, p < .0001 (see table 5.6). Post-hoc testing revealed that the easier tasks with Id's equal to 4 and 5 did not produced significantly different means. As displayed in table 5.9 however, the most difficult task, Id = 6 with a tolerance of .25 inches, was found to yield task means that were significantly different from the other two. Increasing the task difficulty from 4 to 5 increased mean task times from 1.89 seconds to 2.15 seconds, a 14 percent increase (.26 seconds). When task difficulty was increased from 5 to 6 the average increase in the mean task times was 2.15 seconds to 2.74 seconds, an increase of 27 percent (.59 seconds). These increases displayed more of an exponential growth rather than a linear one. These results are similar to those found for task difficulty effects on video viewing performance.

Table 5.9 - Post-Hoc Test Results for Task Difficulty/Tolerance for Direct Viewing Performance

alpha = 0.05, degrees of freedom = 10, mean square error = 2.48

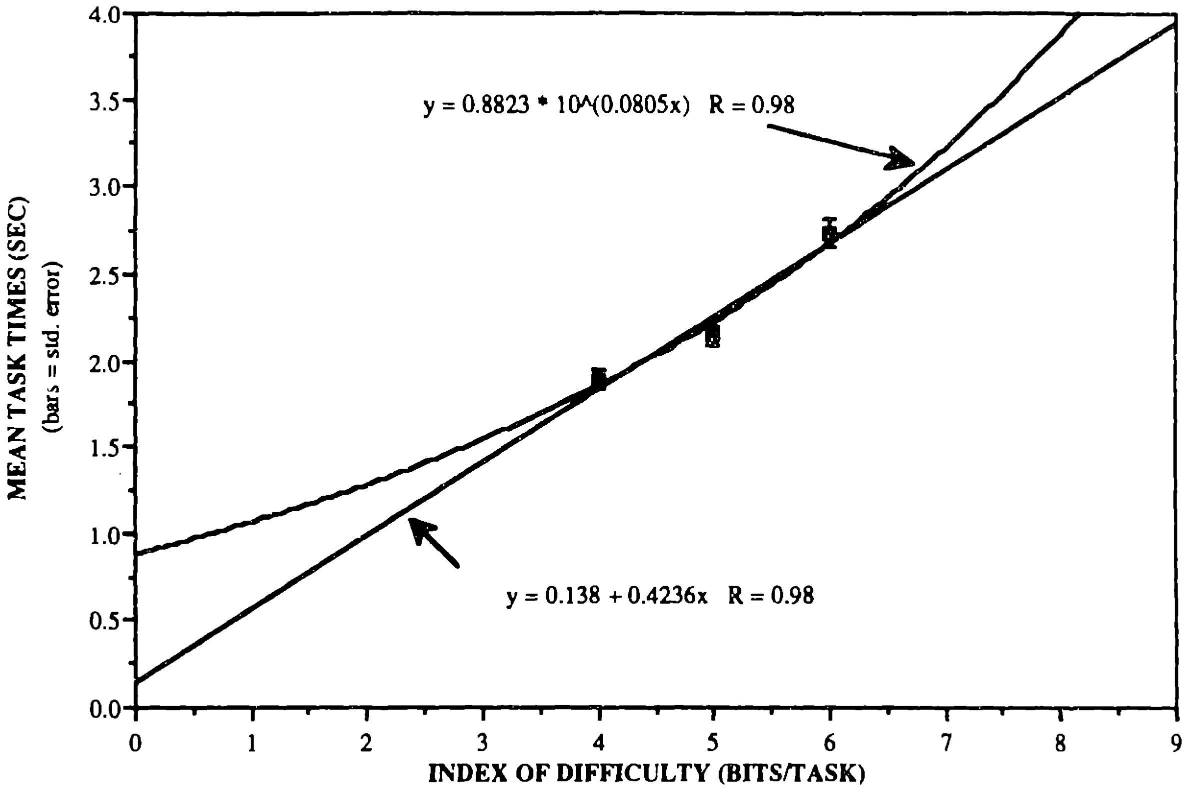
r-value	2	3
critical range	0.262	0.322

Means with the same letter for grouping are not statistically significant.

INDEX OF DIFF.	TOL.	MEAN (SEC.)	STD. ERR.	N	GROUP
6 bits/task	.25 inches	2.74	0.0828	360	A
5 bits/task	.5 inches	2.15	0.0537	360	B
4 bits/task	1.0 inch	1.89	0.0506	360	B

Figure 5.8 graphically displays the effects of task difficulty on direct viewing performance. Both a linear fit, $y=0.138+0.424x$, $R=0.98$, and an exponential fit, $y=0.882*10^\wedge(0.081x)$, $R=0.98$, were performed. The shape of the dispersion of the data and the post-hoc test results suggest that the exponential curve provides a better indication of the performance trends.

FIG. 5.8 - TASK DIFFICULTY EFFECTS ON DIRECT VIEWING PERFORMANCE



5.3.5 DIRECTION EFFECTS

As was the case with the video viewing results, direction did not make a significant difference in task times, F(1,5) = .53, p > .05. For each task, the times for one direction were about the same as those for the other.

5.3.6 INTERACTION OF DISTANCE WITH FORCE FEEDBACK

The interaction of distance with force feedback was found to make a significant difference in performance times as indicated by the analysis of variance results outlined in table 5.6, $F(2,10) = 6.91$, $p < .015$.

Table 5.10 - Post-Hoc Test Results for Interaction of Distance/Viewing Angle and Force Feedback for Direct Viewing Performance

alpha = 0.05, degrees of freedom = 5, mean square error = 6.46

r-value	2	3	4
critical range	0.690	0.871	0.989

Means with the same letter for grouping are not statistically significant.

FFB	DIST. (FT.)	V.A. (DEG.)	MEAN (SEC.)	STD. ERR.	N	GROUP
YES	4	3.28	1.50	0.0338	180	A
NO	4	3.28	2.33	0.0897	180	B,C
YES	8	1.64	1.79	0.0495	180	A,B
NO	8	1.64	2.74	0.0903	180	C
YES	12	1.09	1.85	0.0553	180	A,B
NO	12	1.09	3.32	0.133	180	D

FFB = force feedback condition, DIST = viewing distance, V.A. = viewing angle, STD ERR = mean standard error, N = number of observations

For the Newman-Keuls post-hoc tests, the mean square used was from the force feedback error term in order to use the most conservative post-hoc tests. Table 5.10 shows the results of the post-hoc tests with the associated mean task times. At all three distances, force feedback made a significant difference.

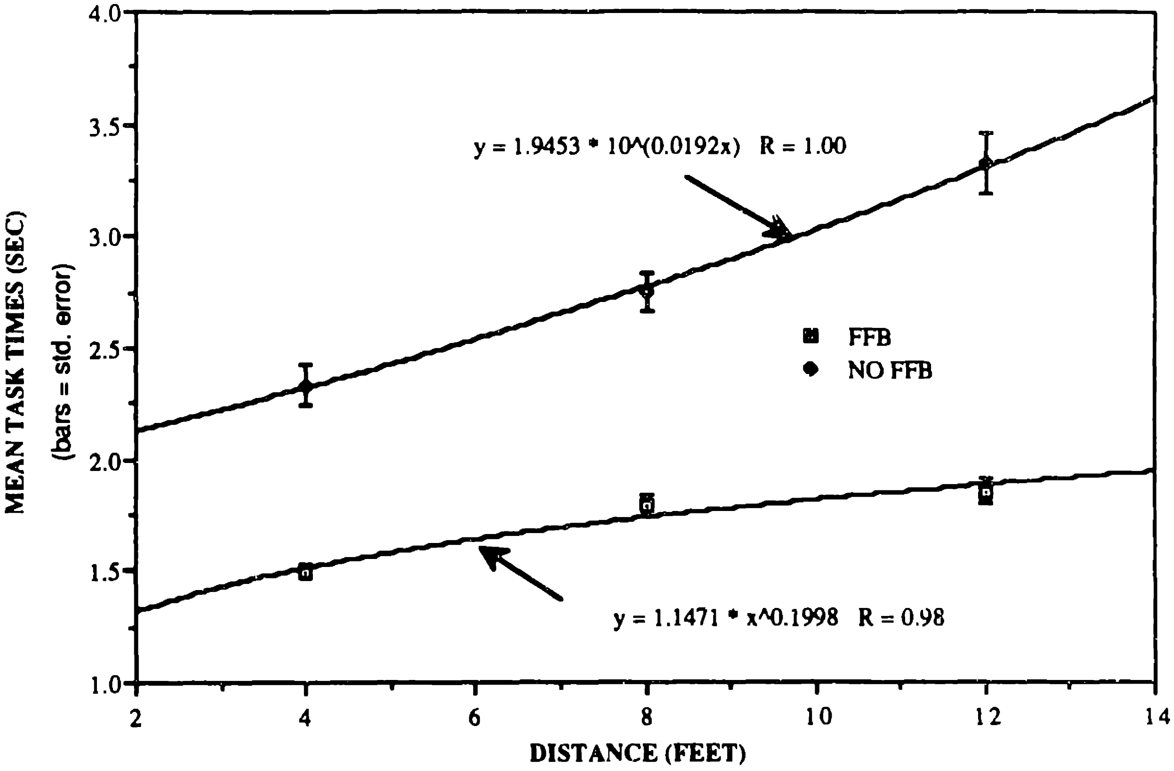
While operating with force feedback, moving further away did not significantly increase task times. Further, force feedback was able to improve performance at the furthest distance by a margin large enough to make the task times not significantly different from those observed for the closest distance without force feedback.

While performing tasks without force feedback, the four foot distance was not significantly different from eight feet. However twelve feet without force feedback was significantly different from the other two distances without force feedback.

Figure 5.9 provides graphs of the curves for the mean performance times with and without force feedback. As the figure displays, the gap between the means for task times with and without force feedback widens as distance increases. This suggests that over larger distances force feedback has a greater impact on improving performance times than at closer distances.

An interesting trend in figure 5.9 is that the two curves appear to behave differently. Without force feedback the data seem to have an exponential tendency, $y=1.95*10^{(0.0192x)}$, R=1.00. This shows that the change in distance from eight feet to twelve feet increased time more than changing distance from four to eight feet. With force feedback the data appear to behave logarithmically, $y=1.15*x^{0.200}$, R=0.98. This logarithmic nature and the post-hoc results suggest that force feedback had a stabilizing effect on mean task times regardless of distance.

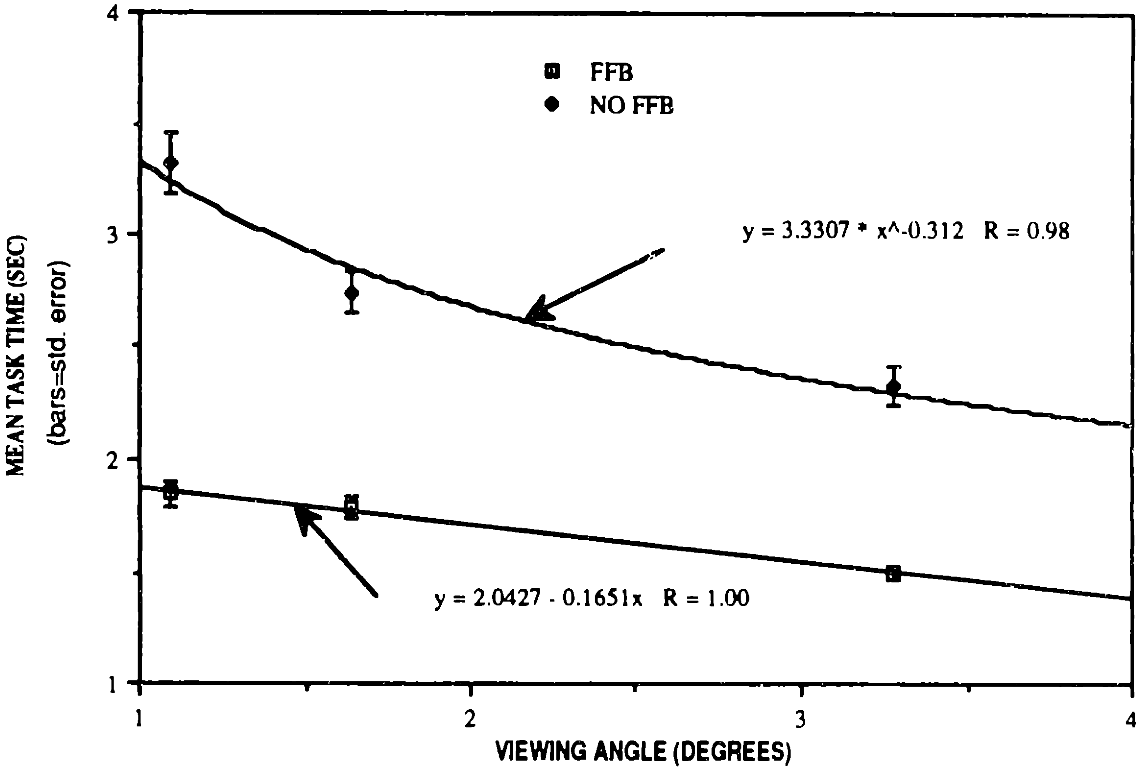
FIG. 5.9 - INTERACTION OF DISTANCE & FORCE FEEDBACK



5.3.7 INTERACTION OF VIEWING ANGLE WITH FORCE FEEDBACK

The interaction between viewing angle and force feedback is exactly the same as the distance and force feedback interactive effects, F(2,10) = 6.91, p < 0.015 (table 5.6). The post-hoc tests also reveal the same results and are displayed with the associated viewing angles in table 5.10. Figure 5.10 graphically shows the interactions of viewing angle and force feedback, e.g., the two curves appear to behave differently. The data for performance with force feedback suggest a linear relationship, y=2.04-0.165x, R=0.98; without force feedback a more logarithmic relationship was observed, y=3.33*x^-0.312, R=.98.

FIG. 5.10-INTERACTION OF VIEWING ANGLE & FORCE FEEDBACK



5.4 VIDEO (30 FPS) AND DIRECT (8 FT.) RESULTS

To determine the difference between performing tasks with direct vision or with the video monitor, video at thirty frames per second and direct viewing at a distance of eight feet were compared. Thirty frames per second was selected for this analysis because it produces fusion at the illumination levels used. The eight foot distance was selected because it produced a viewing angle of 1.64 degrees, effectively the same angle that the subjects were working with while performing the tasks with a video monitor. Thus comparing the 30 fps video viewing performance with the eight foot distance direct viewing performance allows comparison between the two environments with similar frame rates and viewing angles. The major objective was to determine the impact that stereo vision and other characteristics of the direct viewing environment would have on performance as compared to the video viewing environment.

Table 5.11 - Analysis of Variance Results for Variables and Interactions With Statistical Significance for
Video (30 fps) and Direct (8 ft) Viewing Performance

SOURCE	DF	SUM OF SQ.	MEAN SQ.	F-VALUE	P-VALUE
FORCE FEEDBACK	1	17.7	17.7	202	0.0001
ERROR	5	3.23	0.646		
INDEX OF DIFFICULTY OR TOLERANCE	2	8.52	4.26	36.9	0.0001
ERROR	10	1.15	0.115		

5.4.1 EFFECTS OF FORCE FEEDBACK ON PERFORMANCE

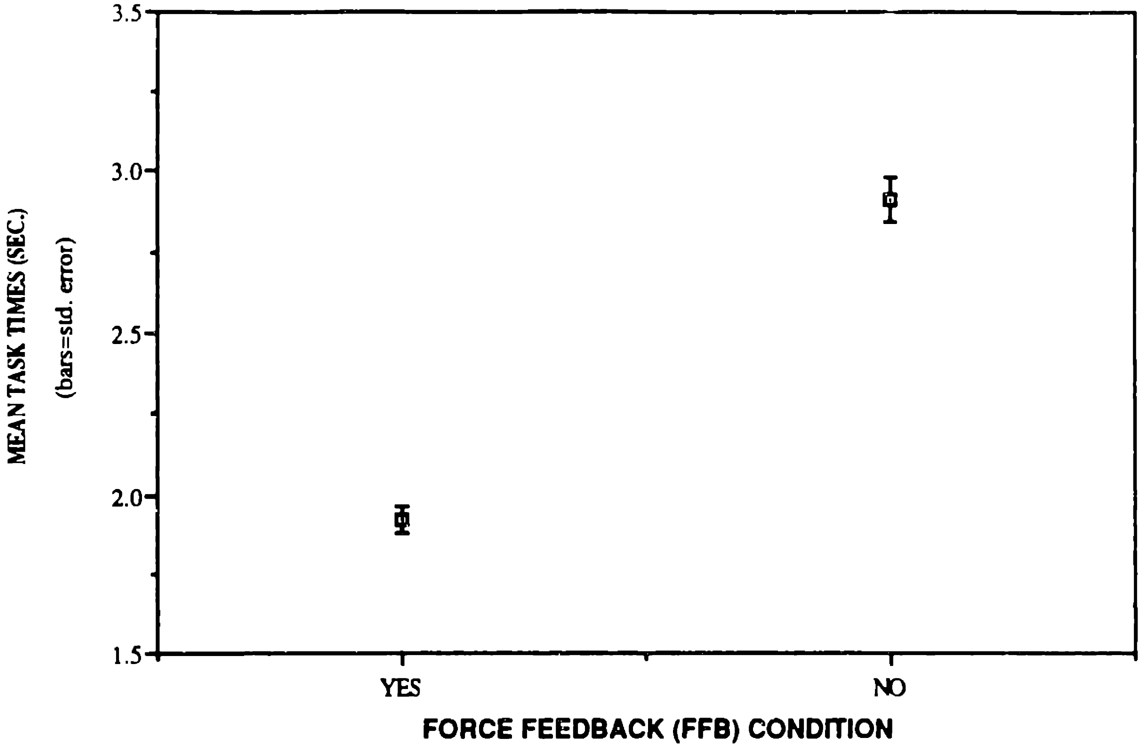
Force feedback was found to make a difference as displayed in table 5.11, $F(1,5) = 202$, $p < 0.0001$. Table 5.12 displays that the mean task time with force feedback was 1.92 seconds and without force feedback the mean task time was 2.91 seconds, indicating that the presence of force feedback improved the mean task times by approximately thirty four percent (.99 seconds). These results are shown graphically in figure 5.11.

Table 5.12 - Results for Force Feedback Effects on
Video (30 fps) and Direct (8 ft) Viewing Performance

Both means are statistically significant

FORCE FDBK CONDITION	MEAN (SEC.)	STD. ERR.	GROUPING
FORCE FEEDBACK	1.92	0.0430	A
NO FORCE FEEDBACK	2.91	0.0676	B

FIG. 5.11 - FORCE FDBK. EFFECTS ON VIDEO (30 FPS) & DIRECT (8 FT.)



5.4.2 TASK DIFFICULTY EFFECTS

Task difficulty was again found to make a difference in performance times, F(2,10) = 36.9, $p < .0001$ (see table 5.11). Table 5.13 shows that post-hoc testing revealed the similar results as previously reported. When task difficulty was equal to 4, mean task time was 2.07 seconds. When difficulty was increased to 5 bits the mean task time increase to 2.29 seconds, representing a 11 percent (.22 seconds) increase in mean time which was calculated to not be a significant difference. The quarter inch tolerance task however had an associated mean task time of 2.89 seconds. This time was a 26 percent (.6 seconds) increase over the task with Id=5 and a 40 percent (.82 seconds) increase in task time from the Id=4 task. Both of these differences were determined to be significantly different by the Newman-Keuls post-hoc analysis.

Table 5.13 - Post-Hoc Test Results for Task Difficulty/Tolerance Effects on Video (30 fps) and Direct (8 ft) Viewing Performance

alpha =0.05, degrees of freedom = 10, mean square error = 1.15

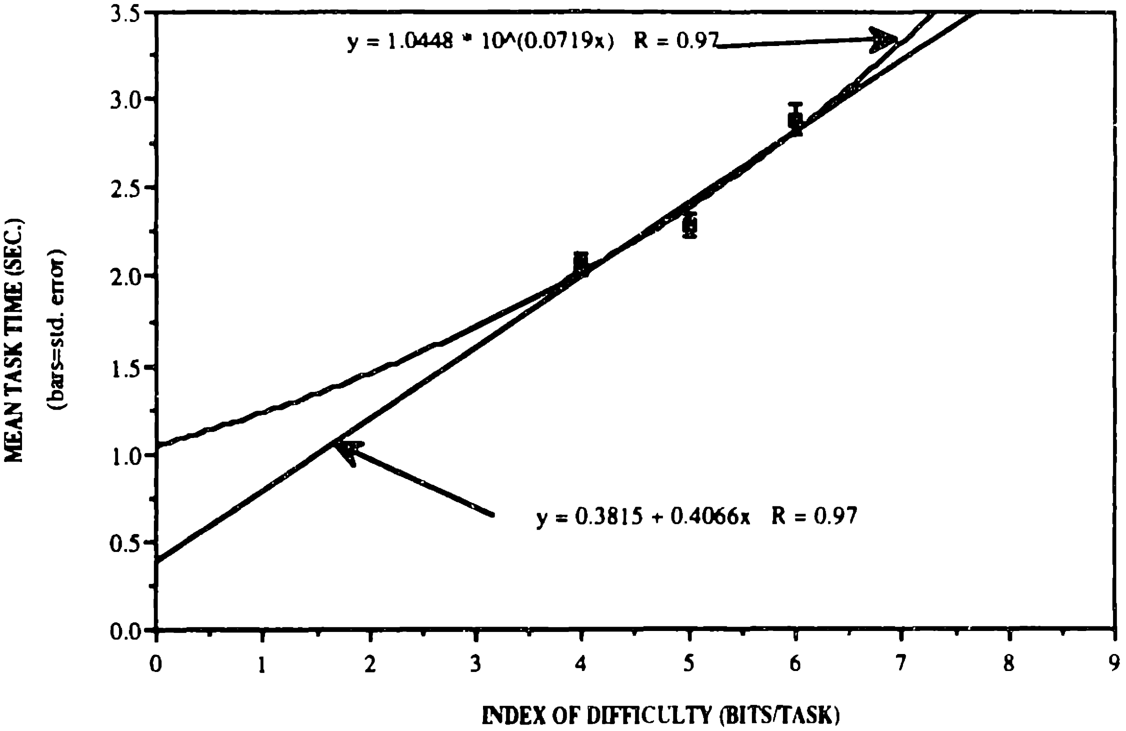
r-value	2	3
critical range	0.219	0.269

Means with the same letter for grouping are not statistically significant.

INDEX OF DIFF.	TOLERANCE	MEAN (SEC.)	STD. ERROR	N	GROUP
6 bits/task	.25 inches	2.89	0.090	240	A
5 bits/task	.5 inches	2.29	0.063	240	B
4 bits/task	1.0 inch	2.07	0.064	240	B

Figure 5.12 shows a graph of the results of the task difficulty effects. The curve fit that best fits the data is the exponential fit where y=1.05*10^(0.0719x), R=0.97, and the error bars represent the standard error of the means. This curve shows that the mean task times are not significantly different for Id=4 and Id=5. When Id is increased to 6 however, there is a significant and increasing rate of change in mean task time. A linear regression was also performed to illustrate the result that Fitts would probably have predicted with the line y=0.382+0.407x, R=0.97. Although the linear fit also appears to describe the data well, this linear relationship was proven to be slightly incorrect from the post-hoc analysis of the data.

FIG. 5.12 - TASK DIFF. EFFECTS ON VIDEO (30 FPS) & DIRECT (8 FT.)



5.4.3 EFFECTS OF VIEW (VIDEO VIEWING VS. DIRECT VIEWING)

Experiments that included an analysis of different views were conducted by Brooks in the Man/Machine Systems Laboratory several years ago. Brooks compared the effects of a single view versus two views of a task for a variety of remote manipulation tasks. He found that the two view condition helped reduce task times for tasks involving precision movements, but had little effect on less precise tasks.[1] Although his views did not directly correlate to stereo vision they did prove that for some tasks, especially those that are more difficult, an additional view or additional visual information could help task performance.

When frame rate and viewing angle were equal, video and direct viewing were not found to be significantly different in task times $F(1,5) = 2.82$, $p > .15$. This indicates that for these experiments stereo vision did not make a difference and that the more important visual variables affecting performance were viewing angle and frame rate.

However, there may be other explanations for view not having a significant effect on mean task time. For example, the effects of stereo vision could be greater at shorter distances than at longer distances. Therefore it is possible that the eight foot distance was too great to utilize the full advantages of stereo vision. This is a topic for future research. Nevertheless the results found in these experiments suggest that the view itself did not have a significant effect on mean task times.

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[1] Thurston L. Brooks, "Superman: A System for Supervisory Manipulation and the Study of Human/Computer Interactions," MIT Masters Thesis, May, 1979, p. 190.

CHAPTER 6 - EXPERIMENTAL CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY OF RESULTS

The use of teleoperators and telemanipulation is necessary for the U.S. space program if the ambitious goals for the space station and those of lunar and planetary exploration are to be met. The experimental results provide some insights into how the use of telemanipulators can be improved.

Some broad conclusions based on the experimental results are:

* Frame rate made a significant difference in performance.

* Force feedback made a significant difference.

* Task difficulty made a significant difference.

* Interaction of frame rate and force feedback made a significant difference.

* Distance/viewing angle made a significant difference.

* Interaction of distance/viewing angle with force feedback made a significant difference.

* Performance using direct vision versus using the video monitor was not significantly different when similar viewing angles and frame rates were present.

* Direction of the movement, going from a small tolerance to a large one or vice-versa, did not make a significant difference.

6.2 VIDEO VIEWING CONCLUSIONS AND RECOMMENDATIONS

The lower frame rates produced significantly lower mean task times. Therefore operating at very low frame rates such as 3 fps should be avoided unless large performance degradations are acceptable. The reduction in mean task times was found to occur at a faster rate when going from 5 fps to 3 fps than when going from 30 fps to 5 fps. This suggests that frame rates between 5 fps and 30 fps may produce performance results that would more likely meet acceptable performance criteria than frame rates below 5 fps. Thus if there is limited bandwidth available for frame rate and depending on the task, reducing frame rate from 30 fps may be acceptable until a cutoff frame rate is reached beyond which performance would be below the accepted level.

Force feedback significantly improved performance at all frame rates. Some scenarios may dictate that force feedback is impossible or undesirable, such as when used with a transmission time delay. But if force feedback is available and the task and environment to do not prohibit its use, force feedback should be utilized.

The experiments showed that as task difficulty as defined by Fitts' index of difficulty increased linearly, mean task times increased at an increasing rate. The two easier tasks did not yield a significant difference in performance. However there were significant differences between the most difficult task and the other two tasks. When increasing task difficulty designers should not assume linear increases in completion time, and should ensure that the difficulty will not be so large as to impede performance by too great an amount.

The interactive effects of frame rate with force feedback indicated that force feedback is particularly useful at low frame rates. Therefore if operating at a very low frame rate is necessary, the presence of force feedback can compensate for the low frame rate. If force feedback is not available, a high frame rate can make up for the degradations due to the absence of force feedback.

6.3 DIRECT VIEWING CONCLUSIONS AND RECOMMENDATIONS

Every distance tested made a significant difference in task times. As distance was increased, task times increased significantly as a linear function. The viewing angle is dependent on the distance and also significantly improved performance when increased. The relation of mean task time to viewing angle was not linear. Increasing the viewing angle made a more drastic improvement in performance when the smallest angle was increased. This suggests that since distance and viewing angle change values at different rates, a large enough viewing angle can compensate for manipulation done over large visual distances.

Force feedback and task difficulty had effects in the direct viewing environment similar to those in the video viewing environment. Force feedback made a significant improvement in task times. This reinforces what was determined earlier: whenever feasible, and in tasks similar to those used here, force feedback can be expected to enhance performance by a significant margin. The two less difficult tasks did not produce significantly different means, but the most difficult task did. With linearly increasing task difficulty, task times increased at an increasing rate rather than a linear one.

The interaction of viewing distance or viewing angle with force feedback showed that over large distances (small viewing angles), force feedback can yield a larger improvement in performance times than at shorter distances (larger viewing angles). This suggests that if manipulation over a large distance or with a small viewing angle is provided to the operator if possible. One would also expect that performance will be degraded more at smaller angles and no force feedback than it would be if force feedback were present.

If a manipulator without force feedback were being used, and direct vision yielded a small viewing angle, it would be wise to use video transmission to provide a larger viewing angle. Although the video may not provide stereo vision, performance would probably be improved with the larger viewing angle. Thus if a choice is given between direct viewing with a small viewing angle against video viewing with a high frame rate and larger viewing angle, video viewing could be the wiser choice.

If there were no force feedback, it would also be important to have the video transmission be at a higher frame rate. If a 30 fps frame rate were too costly, it may be possible to reduce frame rate without harming performance by a great margin. This is especially true if force feedback is present.

Whenever force feedback is possible, it should be implemented. Force feedback was found to make up for many of the performance degradations due to decreased feedback in the visual feedback channel. Force feedback was even found to have a stabilizing effect. When distance was increased (viewing angle decreased) with force feedback, there was not a significant increase in task times. Therefore whenever visual feedback conditions are extremely poor and cannot be improved, the use of force feedback could very well improve performance times to acceptable levels.

As tasks become increasingly difficult, designers should not assume linear increases in task times. Task times can increase at increasing rates. This also suggests that beyond certain difficulty measures, performance time can increase beyond acceptable ranges.

Further research that includes more frame rates, viewing distances, and tasks is necessary. For any manipulation task the effects of the different feedback variables will be unique to the task, making generalizations inaccurate. However the conclusions presented here indicate that task difficulty, force feedback, and the visual feedback parameters of frame rate and distance (or viewing angle) all can have significant effects on human performance for telemanipulation. Therefore these variables should be balanced as recommended in this chapter so as to provide sufficient information for the human operator to perform effectively.

CHAPTER 7 - POLICY ENVIRONMENT

7.1 POLITICAL MOTIVATION

If the U.S. will succeed with its planned Space Station and the many other planetary, lunar, and Earth orbiting missions it hopes to undertake in the future, the use of robotics including teleoperators must be a major element of U.S. space policy. As discussed in Chapter 2, automation and robotics can increase productivity, lower operating costs, increase flexibility, improve reliability, perform tasks unsuited to humans, and reduce hazards for both humans and spacecraft. Further, developing new technology has been the backbone and driving force in the U.S. economy. NASA was established to help the country improve its technology base by conducting space related research and development (R&D) programs and having these technologies stimulate the economy by spinning-off into U.S. industry. To promote these goals further, the White House recently has released new space policy guidelines that highlight the importance of U.S. leadership in space.[1]

With the coming of the U.S. space station, automation and robotics (A&R) have been the focus of many governmental and trade studies. Four of these studies are discussed in Chapter 8. The use of teleoperators in space and the integration of teleoperator systems within the space station have been priority issues for these study groups. Some of the motivation behind these studies has been provided from national and Congressional interest in making the space station a showcase of advanced A&R for the benefit of U.S.

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[1] Craig Covault, "Space Policy Outlines Program to Regain U.S. Leadership," Aviation Week & Space Technology, February 22, 1988, pp. 20-21.

industrial competitiveness.[2] Congressional interest is driven by an awareness of the benefits from advancements being made in electronics, computers, industrial automation, robotics, knowledge engineering, and related fields.[3] NASA and Congress are trying to make the space station program into a user and visible stimulator of new technology advances. Their goals include determining the extent to which the space station can become both a testbed and a showcase of advanced industrial automation technology.[4]

7.2 ECONOMIC FEASIBILITY

The long-term benefits of using advanced automation and robotics should far exceed the initial outlays necessary to begin the program. Figure 7.1 shows that the cumulative value of crew time saved should exceed the cumulative cost of A&R equipment in approximately three years.[5] Boeing conducted this study and based its conclusions on the information in figure 7.2 which shows the increase in available crew time for scientific research due to a large use of A&R for operations and maintenance.[6]

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[2] Martin L. Reiss, "Automation and Robotics and the Development of the Space Station - U.S. Congressional View," AAS Paper 85-664, pp. 531.

[3] David R. Criswell, "Robotics and the Space Station," Robotics, volume 1, 1985, p. 203.

[4] Office of Technology Assessment (OTA), "Automation and Robotics for the Space Station: Phase B Considerations, An OTA Staff Paper," 1985, p.1.

[5] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p.4.

[6] NASA ATAC, Progress Report 3, p. 13.

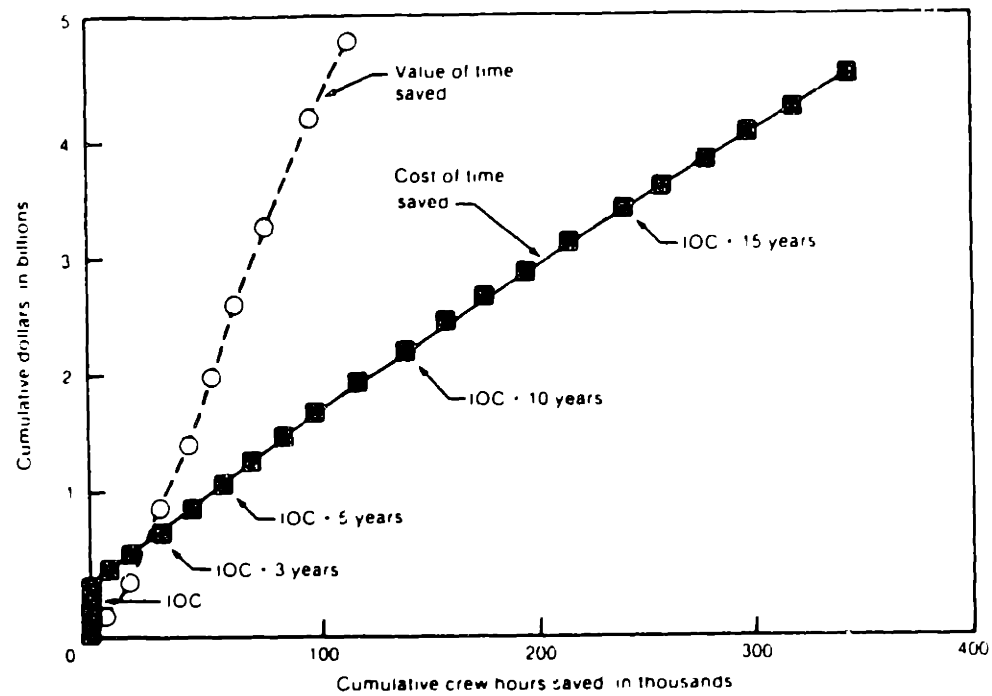

Figure 7.1 - Life cycle benefits of advanced automation and robotics versus initial costs. Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p.4.

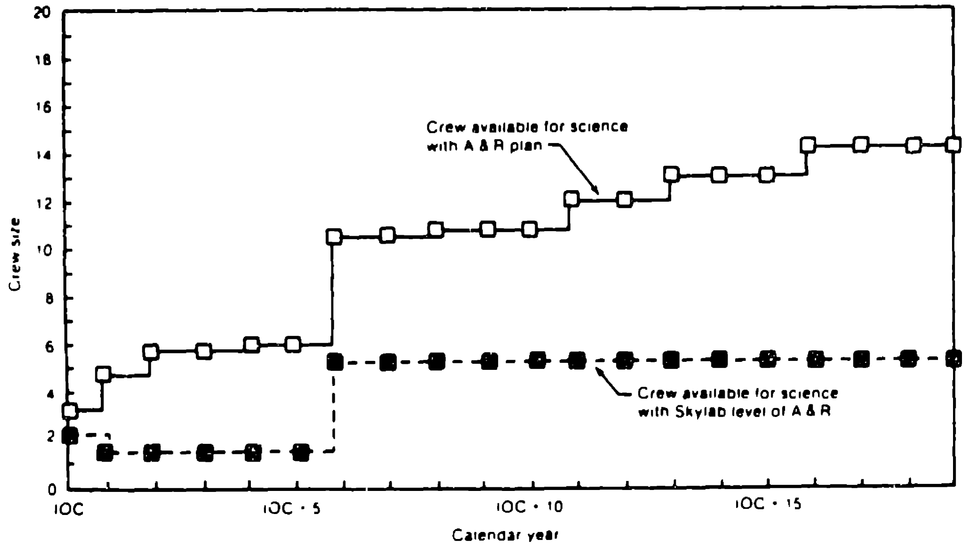

Figure 7.2 - Crew time available for scientific work depends on level of automation and robotics on the space station.
Source:NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p.13.

McDonnell-Douglas estimated the initial cost and annual benefit for using A&R on the space station. As figure 7.3 shows, significant benefits can be realized in a one year benefit period.[7]

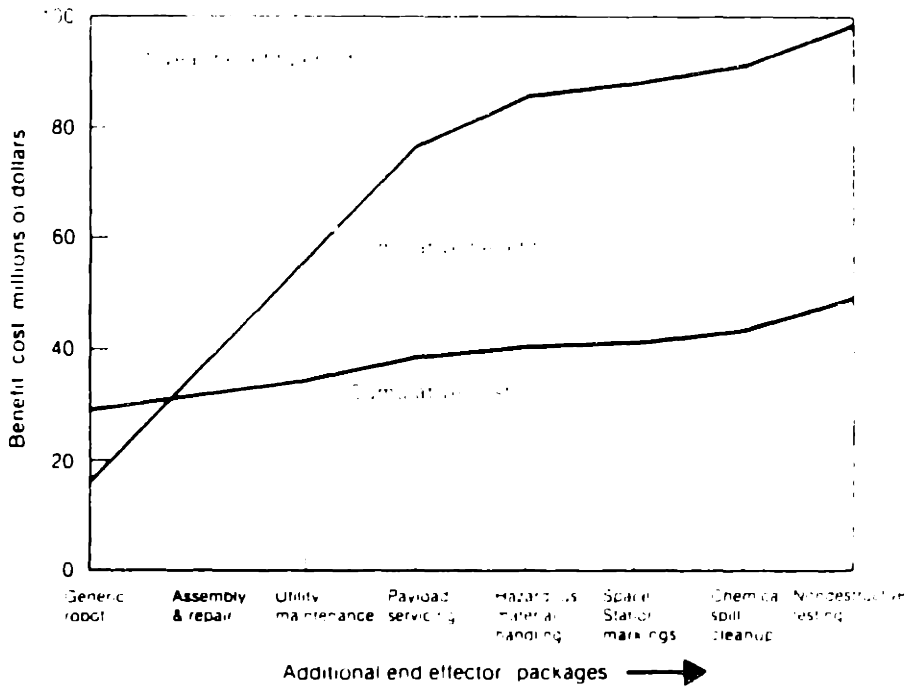

Figure 7.3 - A&R provides favorable cost/benefit ratios in terms of increased productivity on the space station. The overall benefit increases with additional applications.

Source: Source:NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p.12.

These industry studies indicate that advanced A&R on the space station could provide substantial economic and scientific benefits for space exploration. Further these

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[7] NASA ATAC, Progress Report 3, p. 12.

results only include space related benefits. They do not include potential economic benefits from technology transfer to U.S. industries on Earth.

7.3 SPACE ROBOTICS LEGISLATION

The statutory authority behind the major interest in the uses and capabilities of A&R on the space station was provided by Public Law (PL) 98-371 which included the following legislation:

> "Provided further, that the [NASA] Administrator shall establish an Advanced Technology Advisory Committee (ATAC) in conjunction with NASA's Space Station program and that the Committee shall prepare a report by April 1, 1985 identifying specific space station systems which advance automation and robotics technologies, not in use in existing spacecraft, and that the development of such systems shall be estimated to cost no less than 10 percentum of the total space station costs."[8]

In response to a March, 1984 exploratory workshop conducted by OTA on the use of automation and robotics in the space station program, the Senate Committee on Appropriations in Report 98-506 recommended that NASA take the following action to lead the effort in space station R&D for A&R:

> ...the Senate bill requires ... a NASA automation report. This report and the ongoing NASA-sponsored automation study are expected to be completed no later than April 1, 1985.

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[8] U.S. Congress, "National Aeronautics and Space Administration Research and Development, 98 Stat 1227, Research and Program Management Report," Public Law 98-371, 98th Congress, July 18, 1984.

> "The Committee also expects the contractors (i.e., the Space Station Contractors) to devote a significant portion of their effort pursuing the study of automation and robotics technologies identified in the technologies and increasing their terrestrial application."
>
> "The Committee acknowledges the need to pursue a manned space station; however, the Committee believes that NASA needs to pursue the areas of automation and robotics more vigorously. Consequently, the bill language is intended to assure that such technologies are indeed made an integral part of the planning and development for a manned space station."[9]

The impact of the legislation quoted above from PL 98-371 and Report 98-506 has been a series of studies, to be discussed in Chapter 8, and an emphasis on developing A&R capabilities for the space station. This has made NASA, its contractors, Congress, and related governmental agencies extremely interested in research related toward increasing the knowledge base and advancing the state of the art in teleoperation and remote manipulation.

7.4 TECHNOLOGY TRANSFER TO U.S. INDUSTRY

The Space Act of 1958 directed NASA to have as one of its major organizational goals the transfer of technology to non-space sectors of the U.S. economy.[10] The Space Act was amended in 1979 directing NASA to also assist in bioengineering research, development, and demonstration programs designed to alleviate and minimize the effects of

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[9] U.S. Congress, Senate Committee on Appropriations, Report 98-506, 98th Congress, 2nd Session, Calendar No. 967.

[10] U.S. Congress, "Space Act of 1958," Public Law 85-568, 85th Congress, July 29, 1958.

disability. To help improve the transfer of technology from National agency research to industry, universities and other government agencies, the Stevenson-Wydler Technology Innovation Act of 1980 was made into law.[11]

Bill HR 5713, authorizes funding for the space station and is accompanied by report 98-867 which states: "The conferees both intend and expect that the technologies of Space Station automation and robotics will be identified and developed not only to increase the efficiency of the station itself but also to enhance the Nation's technical and scientific base leading to more productive industries here on Earth."[12]

The potential technologies that the space station could develop and their applications in terrestrial environments as identified by ATAC are listed in table 7.1. For intelligent robot applications, ATAC identified the industrial sectors listed in table 7.2.

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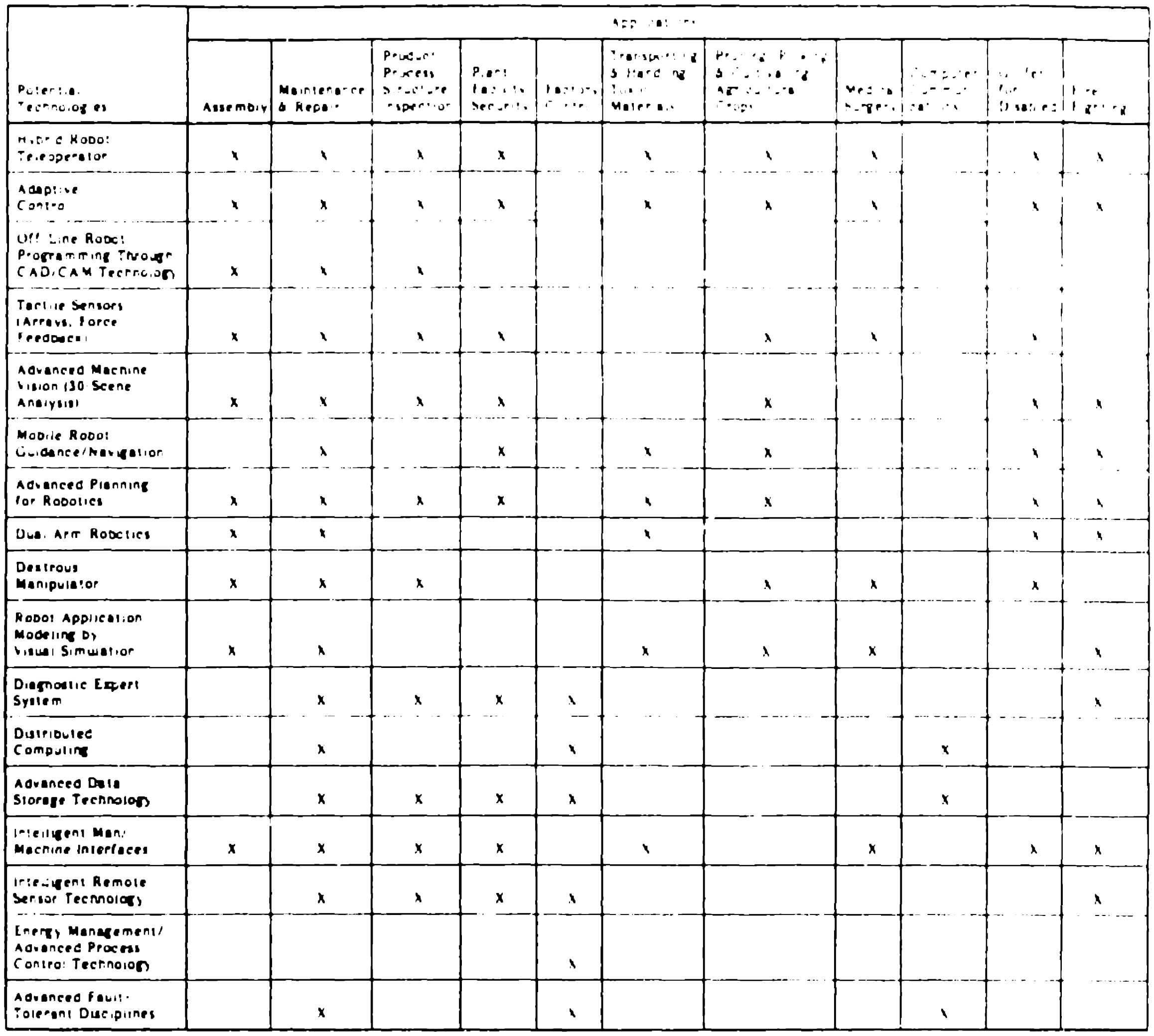
[11] U.S. Congress, "Stevenson-Wydler Technology Innovation Act of 1980," Public Law 96-480, 96th Congress.

[12] U.S. Congress, report 98-867, bill HR 5713.



Potential Technologies	Applications										
	Assembly	Maintenance & Repair	Product Process Structure Inspection	Plant Facility Security	Factory Control	Transporting & Handling Toxic Materials	Producing, Picking & Cultivating Agriculture Crops	Medical Surgery	Computer Communications	Aids for Disabled	Fire Fighting
Hybrid Robot Teleoperator	X	X	X	X		X	X	X		X	X
Adaptive Control	X	X	X	X		X	X	X		X	X
Off Line Robot Programming Through CAD/CAM Technology	X	X	X								
Tactile Sensors (Arrays, Force Feedback)	X	X	X	X			X	X		X	
Advanced Machine Vision (3D Scene Analysis)	X	X	X	X			X			X	X
Mobile Robot Guidance/Navigation		X		X		X	X			X	X
Advanced Planning for Robotics	X	X	X	X		X	X			X	X
Dual Arm Robotics	X	X				X				X	X
Dextrous Manipulator	X	X	X				X	X		X	
Robot Application Modeling by Visual Simulation	X	X				X	X	X			X
Diagnostic Expert System		X	X	X	X						X
Distributed Computing		X			X				X		
Advanced Data Storage Technology		X	X	X	X				X		
Intelligent Man/Machine Interfaces	X	X	X	X		X		X		X	X
Intelligent Remote Sensor Technology		X	X	X	X						X
Energy Management/Advanced Process Control Technology					X						
Advanced Fault-Tolerant Disciplines		X			X				X		

Table 7.1 - Potential technologies developed for the space station and their terrestrial applications.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Volume II - Technical Report, March, 1985, table 7.

Settings	**Uses**
Factories (manufacturing, light industry)	Welding, machining, painting, molding, assembly, inspection, repair, loading, packaging
Offices and institutions (hospitals, schools, prisons)	Distribution (mail, supplies, food), cleaning (floors, windows, trash)
Undersea	Surveying, search and rescue, cable laying, construction, extraction
Mining; oil and gas	Extracting, drilling, rescue (firefighting, boring), processing
Nuclear power plants	Maintenance, emergency operations
Agriculture	Harvesting, planting, irrigation, fertilizing, weed and pest control
Construction	Excavations, structure erection and demolition
Home	Aiding elderly or handicapped

Table 7.2 - Potential intelligent robot applications in the U.S. economy.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy," Volume I - Executive Overview, NASA Technical Memorandum 87566, March,1985, p.18.

The Automation and Robotics Panel (ARP) cited many potential areas for technology transfer into the external arenas for telerobotics. These include:

* Toxic and Radioactive Materials and Hostile Environments - Telerobots can be used to perform tasks in harmful environments such as maintenance, inspection, or rescue, and handle dangerous materials such as radioactive material, toxic gases, biochemicals, or other pollutants.

* Construction Industry - Operations such as sand-blasting, spray painting, welding, loading, unloading, and manipulating heavy objects, especially in large projects such as dams and bridges, would be greatly augmented with teleoperators.

* Private and Public Services - Window washing, toxic waste removal, firefighting, and a number of other dangerous activities could be made less dangerous to humans by utilizing teleoperators.

* Repair and Maintenance of Machines - Telerobots could perform a multitude of repair and maintenance tasks. This would be especially desirable in dangerous or inhospitable regions such as space, deep seas, deep mines, or the polar regions.

* Military - Military applications for telerobots include both maintenance and repair in undesirable locations, and also using telerobots for defense purposes such as reconnaissance, surveillance, and mine disposal.

* Agriculture - Robots could be used for undesirable tasks such as pruning or cultivation, materials handling tasks, and handling of farm animals.

* Applications for the Aged, Infirm, and Disabled - Robotic devices could help the physically disabled by freeing them from the need for constant human care and allowing them to become involved in more every day activities.[13]

If the technologies that are hoped to be developed in space receive proper funding and other necessary resources, it is reasonable to expect that they will be adaptable to industries on Earth. Additionally, there is evidence that automation will not replace workers but to the contrary would improve working conditions, wages, and create more jobs.[14]

The spinoffs from space automation & robotics mentioned here are only a portion of the potential benefits for the U.S. economy. New applications will surely arise as a result of the advanced R&D and applications for space telerobotics.

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[13] Automation & Robotics Panel, Automation & Robotics for the National Space Program, California Space Institute, University of California, NASA Grant NAGW629, February 25, 1985, pp. 96-99.

[14] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy," Volume I - Executive Overview, NASA Technical Memorandum 87566, March, 1985, p. 17.

7.5 INTERNATIONAL TECHNOLOGY TRANSFER

Congress has expressed concerns over the potential impact of work done by the international partners of the space station in automation and robotics. Canadians built the remote manipulator system on the space shuttle. Canada has also been planning a telerobotic system that will enhance space operations on the space station. The system is the mobile servicing system and is schematically outlined in figure 7.4.[15] Japan's experiment module (JEM) for the space station includes a remote manipulator arm for transport of materials between the logistics module and the exposed facilities (see figure 7.5).[16] Both Canada are international space station partners with intense interests of using remote manipulators in space.

Congress has established guidelines that all participation in these areas should be in proportion to overall participation, and that the U.S. should be the country to benefit most from the advanced development of technology on the space station. Guidelines have been established to prohibit the unwarranted transfer of technology between countries, while also defining standards to insure that the elements are compatible.[17] Although the international partners will be using and developing telerobotics technology on the space station, it is apparent that such activity will be closely monitored by the U.S.

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[15] NASA ATAC, Progress Report 3, p. 22.

[16] NASA ATAC, Progress Report 3, p.28

[17] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 2, March, 1986. p. 18.

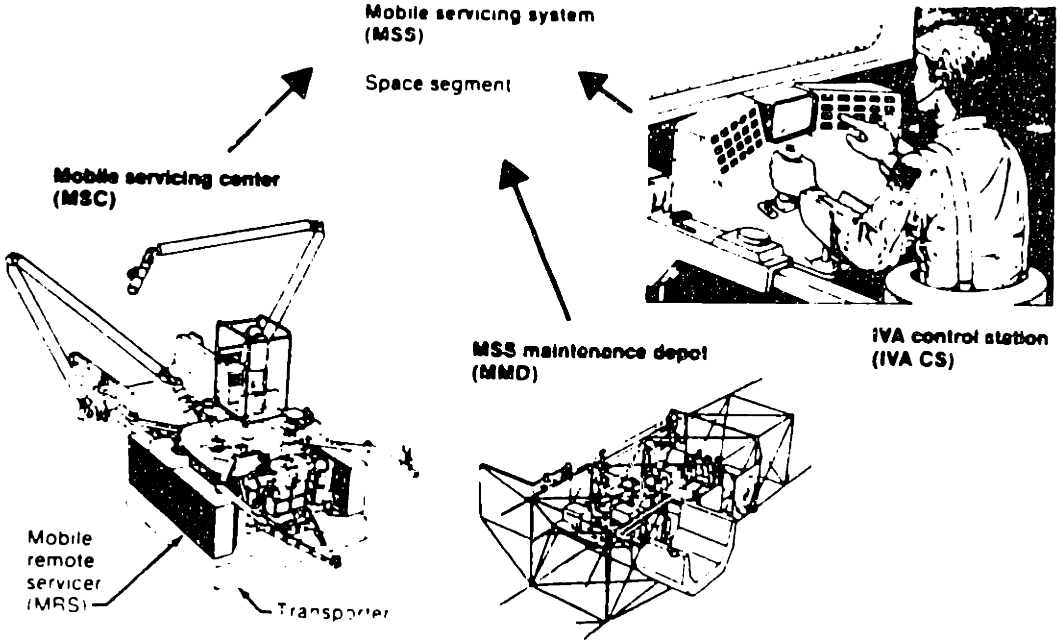

Figure 7.4 - Canadian mobile servicing system components for the space station.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p. 22.

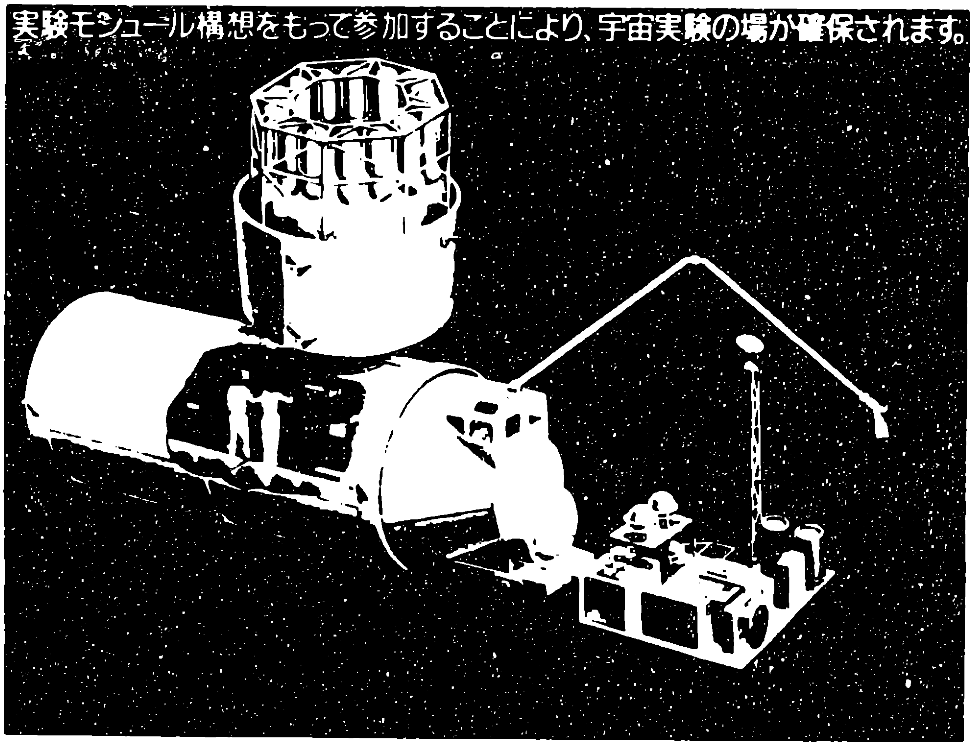

Figure 7.5 - Japanese experimental module (JEM) with remote manipulator.
Source:NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 3, September, 1986, p. 28.

7.6 SPACE COMMERCIALIZATION

U.S. space policy promoted the uses of space resources for commercial ventures, while NASA has continually encouraged industry's participation in the commercial use of space. They have done so by supporting research aimed at commercial applications, allowing easier access to government facilities, offering reduced-rate space transportation for experiments, providing technical assistance, seed money, and occasionally an initial market.[18] In February, 1988, President Reagan ordered a shake-up of U.S. commercial space policy in his fifteen point commercial space initiative that will open up low-Earth orbit to commercial development.[19]

Some past official statements exemplifying the importance and concern over commercial space policy are:

> "The United States Government will provide a climate conducive to expanded private sector investment and involvement in civil space activities....."[20]
>
> President Ronald Reagan
> National Space Policy
> July 4, 1982

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[18] James M. Beggs, "Foreward," in Spinoff 1985 by James J. Haggerty (Washington, D.C.: GPO, 1985), p.1.

[19] Theresa M. Foley, "U.S. Opens Low-Earth Orbit to Commercial Development," Aviation Week & Space Technology, February 22, 1988, pp. 21-22.

[20] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Volume II - Technical Report, March, 1985, p. 109.

"We should establish a policy which would encourage commercialization of space technology to the maximum extent feasible."[21]

Committee on Science and Technology
U.S. House of Representatives Report
April 15, 1983

"The Committee is fully supportive of efforts by the private sector to invest and seek commercial opportunities in space."[22]

Committee on Commerce, Science &
Transportation
U.S. Senate
Report May 16, 1983

"The extent to which past investment in space technology contributes to our future economic well-being and national growth will depend in large measure on policies and actions taken in a spirit of collaboration by the Federal Government and industry."

"Unless the public and private sector join to develop the opportunities presented by new space technologies and unless entrepreneurial forces are engaged more fully, the United States will fall behind in the contest for leadership in space and the economic rewards associated with that position."[23]

National Academy of Public Administration
May 1983 Report

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[21] NASA ATAC, Volume II, p. 107.

[22] NASA ATAC, Volume II, p. 107.

[23] NASA ATAC, Volume II, p. 107.

NASA has had success with space teleoperation spinoffs into terrestrial environments. The space shuttle remote manipulator system made by Spar Aerospace of Canada has had some of its redesigned versions find Earth-use utility in energy and mining applications. Its first spinoff version went into service with Ontario Hydro, a Canadian provincial electric power company. The Hydro manipulator has been employed in refurbishing a nuclear reactor while increasing safety and lowering energy costs. A second spinoff from the arm is the planned joint development, between Spar Aerospace and one of the world's largest nickel producers, of an arm to improve safety and productivity in deep-Earth hard-rock mining.[24]

One area of commercialization for telerobotics is telescience applications. Telescience would enable a researcher or scientist to control his/her experiment or manufacturing process remotely, including ground based operations. This would increase possibilities for space commercialization such as in materials processing.

Another area in space commercialization that could be improved is satellite servicing. Teleoperation could advance the capability to assemble, maintain, and repair satellites in orbit.[25] This would present huge benefits to the commercial satellite industry. An example of a task that is well suited for teleoperators is remote satellite refueling. This type of refueling would extend the life of satellites and keep astronauts out of hazardous environments, especially if the satellite is located in geosynchronous orbit.[26]

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[24] James J. Haggerty, Spinoff 1986 (Washington, D.C.: GPO, 1986), p. 81.

[25] Michael Massimino, "Remote Servicing of a Solar Power Satellite," in Space Manufacturing 6: Nonterrestrial Resources, Biosciences, and Space Engineering, Proceedings of the Eighth Princeton/AIAA/SSI Conference, May 6-9, 1987, eds. Barbara Faughnan and Gregg Maryniak (Washington, D.C.: American Institute of Aeronautics and Astronautics, 1987), pp. 148-152.

[26] Jack E. Pennington, "Space Telerobotics: A Few More Hurdles," Presented at the IEEE International Conference on Robotics and Automation, San Francisco, California, April 8-10, 1986.

TRW identified twelve key A&R technologies to make efficient satellite servicing possible.[27] These results are listed in table 7.3. A free flying telerobot that could perform many of the necessary servicing tasks is shown in figure 7.6.[28]

In a very broad sense, the use of automation and robotics in space will improve space commercialization by improving productivity in space. Increased productivity should mean reduced costs which in turn would allow more commercial space activities to be feasible.[29] These costs have recently been the focus of disputes over space shuttle pricing for many commercial space ventures including the Spacehab commercial space module. Some government agencies were looking to recover operating costs with high prices. NASA was arguing that although operating costs were high, higher prices could jeopardize the future of commercial space activities. Congressional support was behind NASA and it appears that prices will be kept down to an affordable range.[30]

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[27] TRW, "Space Station Automation Study - Satellite Servicing," Volume I, II, Contract NAS8-35081, November, 1984.

[28] Boeing, "Space Station Automation and Robotics Study, Operator-Systems Interface," D483-10027-1, November, 1984.

[29] NASA ATAC, Volume II, p.112.

[30] Theresa M. Foley, "NASA Wins Policy Dispute Over Space Shuttle Pricing," Aviation Week & Space Technology, April 4, 1988, pp. 20-21.

KEY TECHNOLOGY	STATE OF TECHNOLOGY			ENABLING TECHNOLOGY	ENHANCING TECHNOLOGY	PRIORITY RANKING
	NEAR-TERM	INTERMEDIATE	LONGER TERM			
1. DEXTROUS MANIPULATORS, INC., SPECIAL END EFFECTORS	X			X		1
2. SERVICING/AUTONOMOUS SERVICING COMPATIBLE SATELLITES AND PAYLOAD UNITS	X			X		1
3. SPACE-QUALIFIED ROBOTS, ROBOTIC SERVICING		X		X		1
4. DATA SYSTEM SERVICING SUPPORT	X				X	1
5. ADVANCED MAN/MACHINE INTERFACES		X			X	1
6. ADVANCED FLUID TRANSFER SYSTEMS		X		X		1
7. ROBOT-VISION CONTROLLED SERVICING		X		X		1
8. AUTOMATED LOAD HANDLING AND TRANSFER			X		X	2
9. AUTOMATED RENDEZVOUS, BERTHING, AND PROXIMITY OPERATIONS		X			X	2
10. OMV WITH SMART FRONT END		X		X		2
11. KNOWLEDGE-BASED SYSTEM SUPPORT (TROUBLESHOOTING, PLANNING, CONTINGENCY RESPONSE)			X		X	3
12. REUSABLE OTV			X	X		3

Table 7.3 - Satellite servicing aided with A&R technology assessment.
Source:NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy,Vol. II-Technical Report,March,1985,table 5.

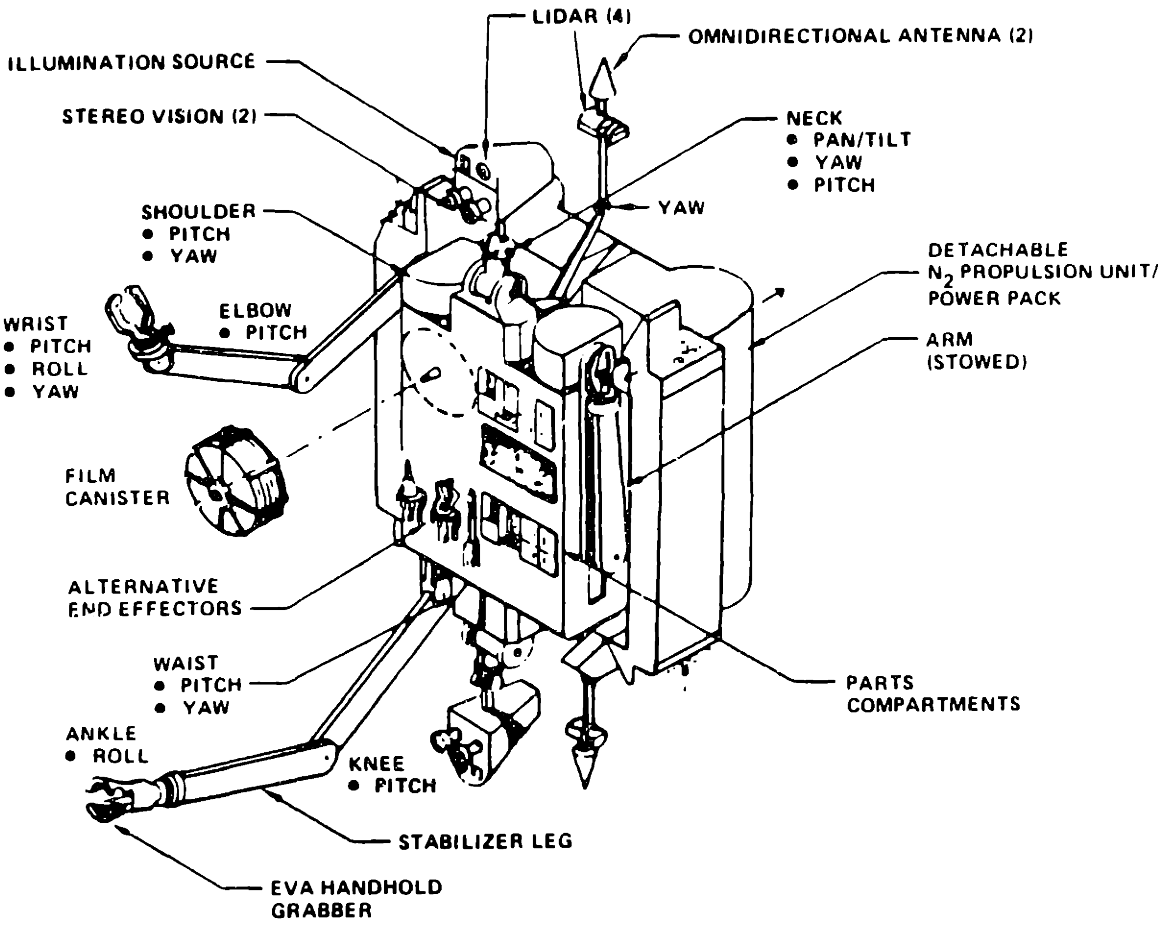

Figure 7.6 - An external robot concept by Boeing.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Vol. II-Technical Report, March, 1985, fig. 21.

There are several other commercial space applications that would require some type of remote manipulation capability in order to be performed efficiently. Automation can allow certain space manufacturing processes or experimental activities to take place without constant monitoring by humans. Operations that are inherently dangerous to humans such as the handling of hazardous materials while growing gallium arsenide crystals (see figure 7.7), can be performed without exposing humans to those dangers. Other operations require precise or repetitive tasks that are more suited to be performed by machines than be human hands. Experiments or operations that will take place on orbiting platforms without the presence of humans will need to be monitored and controlled remotely.[31] An example of this is the proposed Industrial Space Facility that would be a free-flying facility man-tended from the space station.[32]

Therefore, teleoperation can provide flexible support to a variety of commercial space activities. These activities include:

- materials handling in manufacturing
- large-scale space construction
- satellite servicing
- spacecraft servicing
- film retrieval or servicing of Earth-viewing satellites in geosynchronous orbit
- deployment and retrieval of experimental packages at the space station.[33]

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[31] NASA ATAC, Volume II, p.112.

[32] Theresa M. Foley, "U.S. Space Platform Firms Aim for 1991 Service Start," Aviation Week & Space Technology, February 29, 1988, pp. 36-38.

[33] NASA ATAC, Volume II, p.110-111.

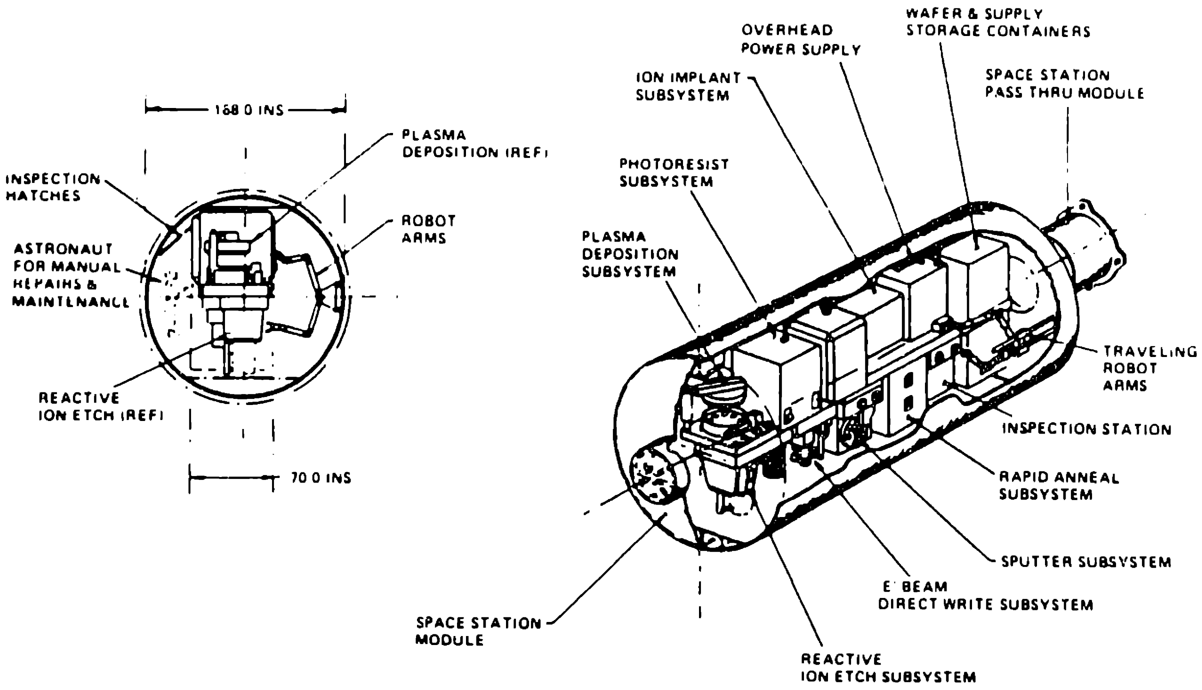

Figure 7.7 - Automated gallium arsenide microelectronics chip processing facility concept by General Electric.
Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Volume II - Technical Report, March, 1985, table 7.

7.7 POLICY ENVIRONMENT SUMMARY

Although teleoperation can pose many benefits for the U.S. space program and the U.S. economy, none of the benefits are possible without a committed space policy to develop these capabilities. Congress wants the space station to become a testbed for telerobotics applications that can help the U.S. position in international industrial competitiveness, and appears willing to support the necessary legislation to bring their goals to fruition. Because of its economic benefits, potential spinoffs, and commercial applications, automation and robotics is deserving of long term commitment from Congress, the White House, NASA, and the industrial sectors of the U.S.

CHAPTER 8 - POLICY STUDIES

8.1 ADVANCED TECHNOLOGY ADVISORY COMMITTEE (ATAC) REPORTS

To help establish A&R as a general purpose technology that can be used to benefit not only the space station but also the U.S. economy as a whole, Congress directed NASA to create ATAC. The ATAC reports have guided NASA in implementing its A&R policy for the space station to meet space station user needs with high productivity and low operating costs. They have also focused on areas important to the commercialization of space.[1] Figure 8.1 displays the methodology for the ATAC study.

Aaron Cohen, the first Chairman of ATAC, cited the following as ATAC's major objectives:

"* Identify potential advances in the state-of-the-art in automation and robotics technologies for use in the space station and to benefit the U.S. economy.

* Provide guidance for NASA space station program managers and prospective space station definition contractors to direct their efforts toward examination of the potential for advancing automation and robotics technologies through their incorporation in the overall development of the space station.

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[1] Aaron Cohen, Statement before the Subcommittee on Science, Technology and Space; Committee on Commerce, Science and Transportation; United States Senate, March 8, 1985.

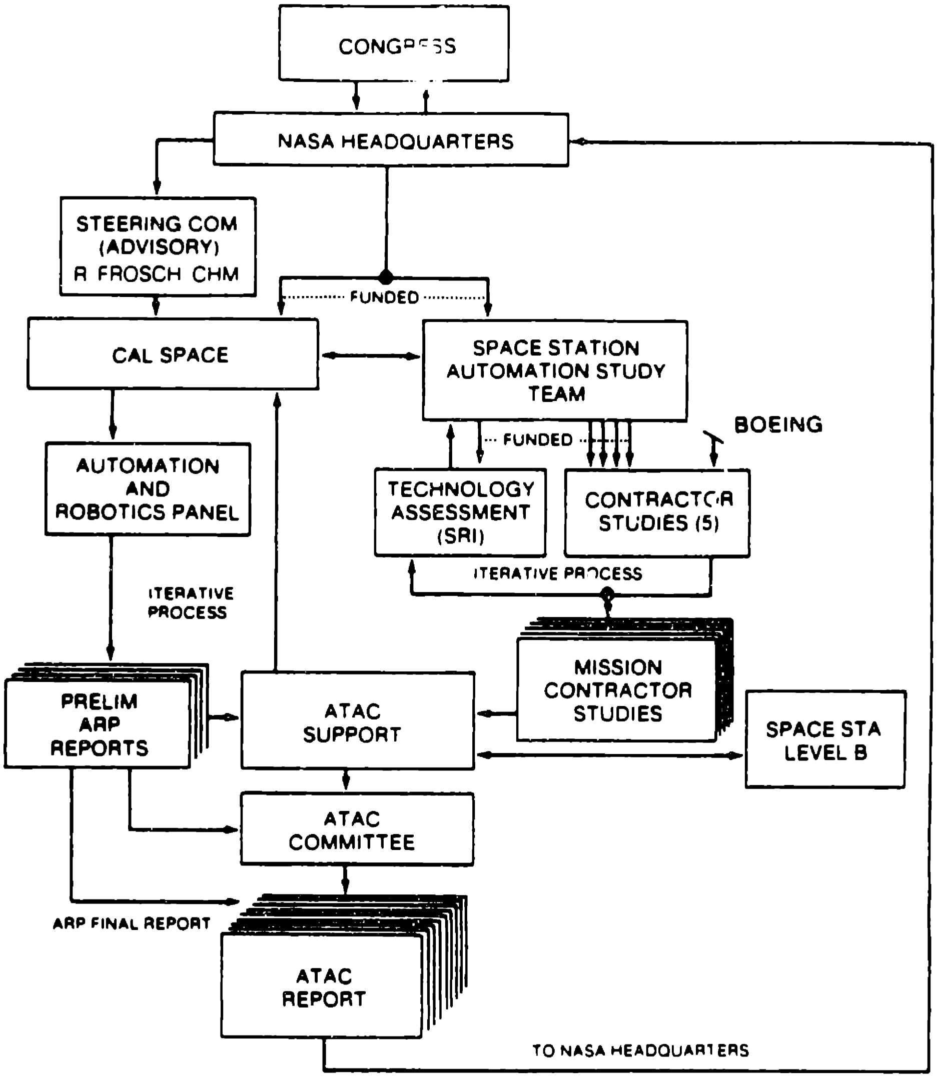

Figure 8.1 - Methodology for the ATAC space station automation study.

Source:Aaron Cohen, Statement before the Subcommittee on Science, Technology and Space; Committee on Commerce, Science and Transportation; United States Senate, March 8, 1985, figure A.

- Document in a single convenient source, important considerations in automation and robotics, specifically:
  - NASA space station engineering and programmatic aspects
  - Recommendations of the academic and industrial community
  - Descriptive and background material on the relevant technology
  - Case studies of applications of advanced automation and robotics
  - Technology projections and research recommendations"[2]

The ATAC reports determined that the necessary A&R technology on the space station could be developed in three ways:

1) NASA being the prime developer
2) NASA adapting for space use technology already developed for terrestrial uses
3) using directly devices used in the defense or commercial sectors.[3]

ATAC identified many benefits that could be incurred from this legislation. For space:

"* Increased productivity - with astronauts functioning as managers on behalf of station users rather than as operators carrying out routine functions.

* Increased responsiveness to innovation - with the automated space station being more flexible and adaptable.

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[2] Cohen, p. 7.

[3] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy," Volume I - Executive Overview, NASA Technical Memorandum 87566, March, 1985, p. 3.

* Lower cost of operations - with highly automated systems that can run at peak efficiency.

* Improved reliability - with machine intelligence contributing to improved detection, diagnosis, repair, and recovery from abnormal situations.

* Greater autonomy - with machine intelligence to support monitoring and control of station systems, thereby lessening reliance on ground support.

* The ability to perform with robots and teleoperators tasks unsuited to humans alone - such as the assembly of large structures.

* A reduced need, because of the use of robots and teleoperators, to expose humans to hazardous situations - such as extravehicular activities, fueling tasks, and servicing satellites in high orbits (where radiation could be harmful)."[4]

For the U.S. economy:

"* A space station more suitable for commercial ventures with flexible and reliable systems and crew time for management actions.

* The application of advances in automation and robotics stimulated by space ventures to terrestrial situations in settings ranging from the factory floor to the homebound elderly and on to the bottom of the sea."[5]

Two basic guidelines were identified by ATAC to facilitate the desired transfer of NASA developed A&R technology to U.S. industry. First, a mechanism should be

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[4] NASA ATAC, Volume I, p. 4.

[5] NASA ATAC, Volume I, p. 4.

established for consideration of industry's needs during the definition and preliminary design phases of the Space Station. Second, NASA's established technology transfer mechanisms should be mobilized whenever possible.[6]

The ATAC committee made recommendations for both basic and augmented research programs. Additional funding levels necessary for the augmented program were initially estimated by the Automation and Robotics Panel (ARP) to be somewhere between 7 and 13 percent of total space station costs. For the basic program the ATAC Committee made eight initial recommendations:

> "1) Automation and robotics should be a significant element of the Space Station Program.
>
> 2) The initial Space Station should be designed to accommodate evolution and growth in automation and robotics.
>
> 3) The initial Space Station should utilize significant elements of automation and robotics technology.
>
> 4) Criteria for the incorporation of A&R technology should be developed and promulgated.
>
> 5) Verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for Space Station use.

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[6] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy," Volume II - Technical Report, NASA Technical Memorandum 87566, March, 1985, p. 95.

6) Maximum use should be made of technology developed for industry and Government.

7) The techniques of automation should be used to enhance NASA's management capability.

8) NASA should provide the measures and assessments to verify the inclusion of automation and robotics in the Space Station."[7]

Five additional recommendations were made for an augmented program:

"9) The initial Space Station should utilize as much automation and robotics technology as time and resources permit.

10) An evolutionary station should achieve, in stages, a very high level of advanced automation.

11) An aggressive program of long-range technology advancement should be pursued, recognizing areas in which NASA must lead, provide leverage for, or exploit developments.

12) A vigorous program of technology transfer to U.S. industries and research and development communities should be pursued.

13) Satellites and their payloads accessible from the Space Station should be designed, as far as possible, to be serviced and repaired by robots."[8]

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[7] NASA ATAC, Volume I, pp. 5-8.

[8] NASA ATAC, Volume I, pp. 8-10.

Proposed program milestones for space station definition and preliminary design are displayed in Table 8-1.

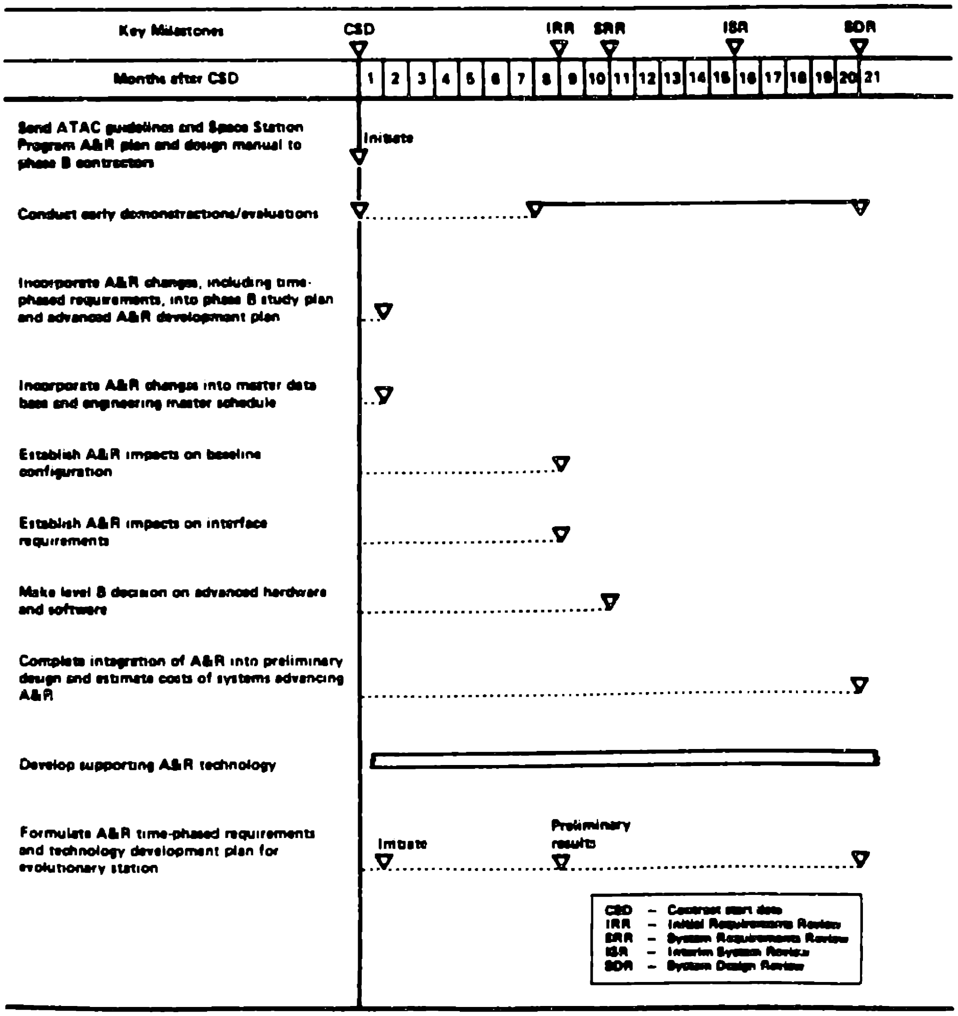

Table 8.1 - Proposed automation and robotics milestones during space station definition and preliminary design.

Source: NASA Advanced Technology Advisory Committee (ATAC), <u>Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy</u>," Volume I - Executive Overview, NASA Technical Memorandum 87566, March, 1985, p. 10.

Some of the space teleoperation goals that ATAC identified which could be assisted by the research from this thesis include:

"* Teleoperation of mobile remote manipulator with collision avoidance.

* Mobile multiple-arm robot with dextrous manipulators to inspect and exchange orbital replaceable units.

* Systems designed to be serviced, maintained, and repaired by robots.

* Primary station control in space with appropriate backup.

* Teleoperators for structures and mechanisms

* Inspection, maintenance, refurbishment, and repair

* Fuel and materials transfer

* Detecting hazardous leaks

* Satellite retrieval and servicing."[9]

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[9] NASA ATAC, Volume I, pp. 11-12.

Proposed criterion	Considerations
Crew and station safety	Need for extravehicular activity Handling hazardous materials
Performance	System weight, volume, and power Accuracy and repeatability of operation Maintainability and reliability Contribution to mission reliability Adherence to customer-imposed requirements
Productivity	Crew productivity, time saved, response-time improvements, extending performance beyond the capability of unaided crew Commonality among functions to be supported Ground operations productivity Training Compatibility of A & R hardware and software with other Space Station equipment and systems
Cost	Non-recurring development costs Operating—i.e., "life cycle" costs
Growth and evolvability	Potential for enhanced capability Application in other space contexts Benefits to the U.S. economy
Risk	Developmental readiness Reliability and maintainability Crew, station, and mission safety Knowledge representability, availability, and ease of validation

Table 8.2 - Criteria for selecting applications of automation and robotics.

Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 1, NASA Technical Memorandum 87772, April-September, 1985, p. 19.

Table 8.2 exhibits ATAC's criteria for selecting applications of robotics in space. Some interim recommendations to enable some applications to be performed with the initial configuration of the space station include:

"* A mobile, extravehicular robot to assist space station personnel in assembly and checkout.

* A rail-mounted intravehicular robot for laboratory service (inspection, maintenance, and repair)

* Stationary "workbench" robots including "smart" hardware such as automated utility containers."[10]

Astronauts who have worked with remote manipulators both while in space on the space shuttle and on the ground with simulators made the recommendations listed in Appendix C about the formulation of robotics policy for the U.S. space program. Their recommendations stressed the use of crew interaction with automation and robotics, and the importance of efficiency to implement the program successfully.[11]

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[10] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 1, NASA Technical Memorandum 87772, April-September, 1985.

[11] NASA ATAC, Progress Report 1, pp. 39-41.

Table 8.3 lists eight levels of technology readiness that ATAC identified in their second progress report for the formation of space policy regarding the use of teleoperators in space.[12]

TABLE 8.3 - LEVELS OF TECHNOLOGICAL READINESS

Readiness Level	Definition
1)	Basic principles observed and reported
2)	Conceptual design formulated
3)	Conceptual design tested analytically or experimentally
4)	Critical function/characteristic demonstration
5)	Component/breadboard tested in relevant environment
6)	Prototype/engineering model tested in relevant environment
7)	Engineering model tested in space
8)	Full operational capability (incorporated in production design)

Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 2, NASA Technical Memorandum 88785, March, 1986, p. 5.

Levels one through four concern building a technology base that incorporates existing technology, research for advanced technology, and current NASA research. Levels five through eight concern identification and development of technologies for the

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[12] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 2, NASA Technical Memorandum 88785, March, 1986.

space station program including advanced development and implementation, research needs, advanced development and implementation of new technology, and initial station provisions for future technology.[13] Figure 8.2 depicts these scenarios.

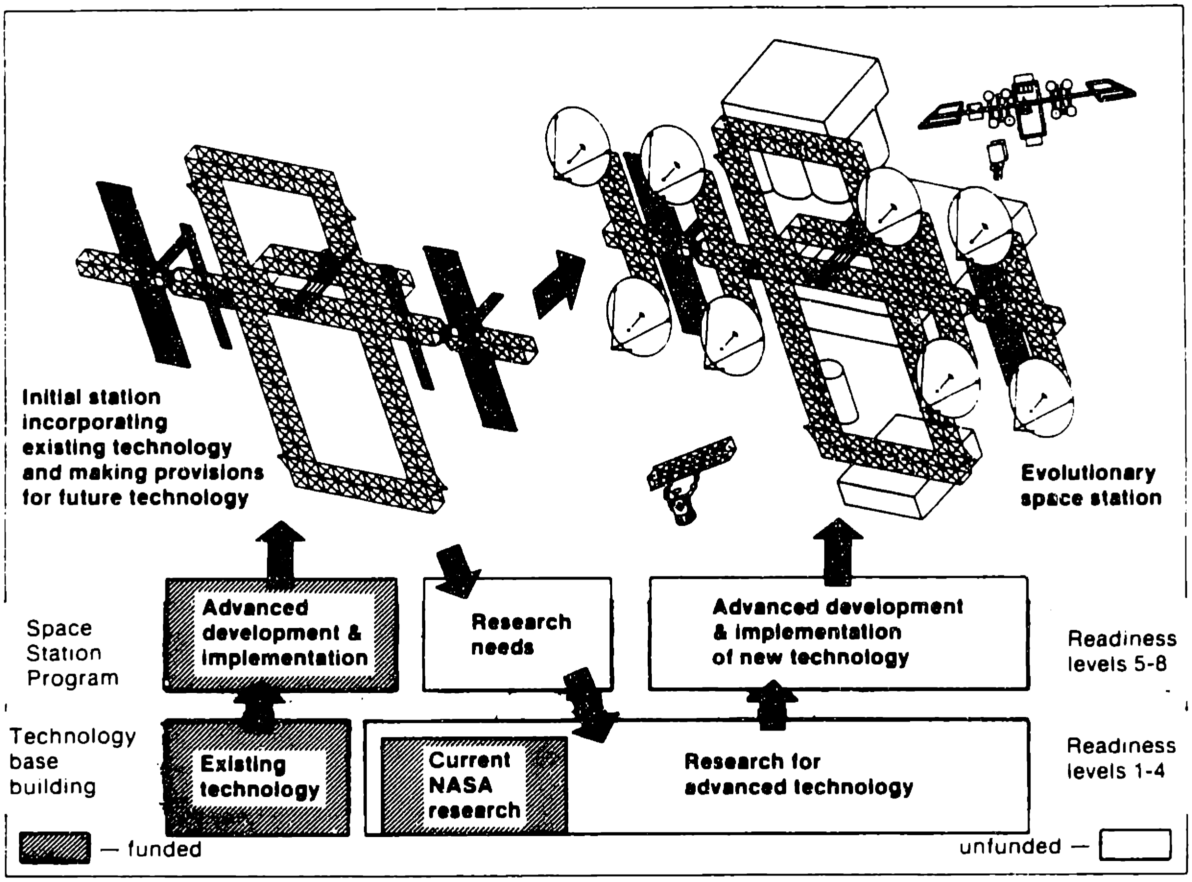

Figure 8.2 - Programmatic approach to the development of automation and robotics leading to full implementation in the evolutionary space station.

Source: NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 2, NASA Technical Memorandum 88785, March, 1986.

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[13] NASA ATAC, Progress Report 2, pp. 5-7.

Despite the advances made, the space station program still needs a space station wide robotics plan to identify required resources and meet user needs.[14] These policy deficiencies were highlighted in a letter by NASA Administrator James Fletcher to Congressman Edward Boland in December, 1986 shown in appendix D.

In its first progress report, for April to September 1985, ATAC identified two most pressing issues:

> "1) Lack of a concrete and specific plan for automating the Space Station which coordinates Space Station design, A&R development, and research for an evolutionary station, and
>
> 2) Lack of resources dedicated to developing new technology for an evolutionary station and moving this automation and robotics into actual use."[15]

Although the goals set by Congress were extremely broad in nature, to advance technology for the space station and consequent benefits for the U.S. economy, ATAC believes that a strong program can realize those goals. Thus an optimal program would be one that could utilize the limited available resources to allow at least a portion of the many great potential applications of remote manipulation to materialize.[16]

ATAC has molded automation and robotics into a critical part of the space station. Through September, 1987 recommendations have emphasized more application definition and defined capabilities of robots and teleoperators in space. They have also emphasized

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[14] NASA Advanced Technology Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 4, NASA Technical Memorandum 89811 May, 1987.

[15] NASA ATAC, Progress Report 1, p. 28.

[16] NASA ATAC, Progress Report 2.

the need for continued emphasis on automation and robotics by Congress and NASA in order to obtain the necessary resources. More recent reports have given updates on specific teleoperation programs such as the Flight Telerobotic Servicer. These developments exemplify NASA's commitment to explore the uses of teleoperators and remote manipulators in space. However much still needs to be done to test the actual capabilities of telerobots in space in order to instill confidence in the technology among those who will be counting on it for remote space operations.

8.2 AUTOMATION AND ROBOTICS PANEL (ARP) STUDY

Since ATAC consists of members from within NASA, the California Space Institute was asked to establish the Automation and Robotics Panel (ARP). Headed by Robert A. Frosch, Vice President of Research for General Motors Corporation and former NASA Administrator, ARP consisted mainly of members from outside of NASA. ARP provided conclusions and recommendations on space A&R independent of, but parallel with, the ATAC reports.[17] The thirty-three member panel was made up of experts from industry, universities, and key government agencies. They were assisted by over sixty non-panel members representing more than thirty major research organizations.[18] In particular the panel focused on identifying advancements that could provide the greatest benefits to both the space station and to terrestrial industries.[19]

The Automation and Robotics Panel (ARP) agreed with Congress in its judgement that NASA could improve effectiveness and reduce space station costs by utilizing automation and robotics. It recognized A&R development for space applications as a vehicle by which the U.S. could regain its world leadership in industrial technology and manufacturing. ARP also determined that the development of space A&R has potentially great benefits for the U.S. economy and the status of U.S. international competitiveness.[20]

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[17] Martin L. Reiss, "Automation and Robotics and the Development of the Space Station - U.S. Congressional View," AAS Paper 85-664, p. 534.

[18] David R. Criswell, "Robotics and the Space Station," Robotics, Volume 1, 1985, p. 203.

[19] Robert A. Frosch, Statement before the Subcommittee on HUD and Independent Agencies of the Senate Committee on Appropriations, United States Senate, March 14, 1985, pp. 2-4.

[20] Automation & Robotics Panel, Automation & Robotics for the National Space Program, California Space Institute, University of California, NASA Grant NAGW629, 25 February 1985, pp. 2-4.

However, ARP also cautioned that the full benefits of space A&R will come to fruition only if NASA and the Congress set the correct policy and allocate appropriate funds to supply the necessary technology base. NASA must take the lead in developing space-unique manipulator systems, while also adapting proven technologies to the space environment.[21]

ARP suggested the following implementation plan for the use of teleoperators and investigating the associated human/machine interface environment:

> Near-term to 1990: Identify teleoperation human factors concerns. Develop and demonstrate force feedback for the shuttle remote manipulator system.
>
> Mid-term, 1991 to 1994: Demonstrate telerobotic control and interface systems that can work efficiently in space including micro-g manipulation, flexible arms, execution monitoring with real-time simulation. Demonstrate multi-arm telerobots for IVA and EVA applications.[22]

For teleoperators and manipulators controlled by humans, ARP identified areas in which NASA could lead, apply leverage, and exploit existing technologies:[3-12]

Lead: Space Manipulators, Materials Handling Technologies, Robot Mobility in Space, Man/Machine Interfaces

Apply Leverage: Robots Sensors/Integration, Reconfigurable & Repairable Robots, High-Level Robot Programming Language

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[21] Automation & Robotics Panel, pp. 2-3.

[22] Automation & Robotics Panel, p. 7.

Exploit Existing Technologies: Terrestrial Robots and Manipulators, Lightweight Motors.[23]

The necessary funding levels for these areas are estimated in table 8.4.

A&R Technology Program: Man/Machine-Robotics

	Category	Baseline Program ($M year)		Minimal Program ($M year)		Delta $M year	Fallback Order
		Research	Demos	Research	Demos		
NASA must *lead*	Space Manipulators	10	2	6	2	4	5
	Materials Handling Technologies	8	2	4	2	4	5
	Robot Mobility in Space	8	2	4	-	6	5
	Man/Machine Interfaces	25	4	11	2	16	4
NASA applies *leverage*	Robot Sensors/Integration	16	4	10	2	8	3
	Reconfig./Repair Robots	3	-	-	-	3	2
	Hi-Level Robot Progrm. Lang.	6	-	-	-	6	1
NASA can *exploit**	Factory Robots	< 1	< 1	-	-	-	-
	Lightweight Motors	< 1	< 1	-	-	-	-

* Examples of potential off-the-shelf purchases.

Table 8.4 - Necessary funding levels for man/machine robotics technology program.

Source: Automation & Robotics Panel, Automation & Robotics for the National Space Program, California Space Institute, University of California, NASA Grant NAGW629, 25 February 1985, p. 42.

Some identified candidates for teleoperated operations include the handling of cryogens, servicing of satellites, cleaning lens elements, replacing hazardous consumable materials, transporting vehicles, and refurbishing and repairing satellites. Another potential area for teleoperation is the establishment and operation of space manufacturing facilities

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[23] Automation & Robotics Panel, p. 42.

for crystal growth, integrated circuit chip fabrication, pharmaceutical production, and the assembly of large space structures.[24]

Telerobots could be implemented in three stages. First, on the space station, manipulators for materials handling and monitoring tasks such as those necessary for the operation of experimental equipment and samples should be implemented. Next, movable robots could be equipped with visual and force feedback to perform more complex tasks such as refueling and maintenance. Lastly free flying telerobots could be used to perform complex operations that would be large distances from the space station.[25]

For an ideal human/machine interface for various remote manipulation capabilities, the teleoperator of the future in space would need to have a high degree of telepresence. Such a system would possess the following characteristics:[3-12]

"* Stereoptic color vision system, slaved to operator head motion.

* Head-mounted vision display.

* Paired 7-degree-of-freedom manipulator arms with force control.

* Force-indicating hand controllers or exoskeleton arms for control.

* Two grapple arms or one docking device.

* Interchangeable end effectors."[26]

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[24] Automation & Robotics Panel, p. 45.

[25] Automation & Robotics Panel, p. 45.

[26] Automation & Robotics Panel, p. 58.

NASA could greatly augment its efforts in developing robotic systems by establishing formal incentive systems to encourage external participation. Extending incentive contracts to companies that guarantee payment for the delivery of certain products, or for development in areas of high risk would appeal to the private sector. For national laboratories cost-plus contracts are the acceptable mechanism by which incentive can be established. Academia incentives would be similar to those of national laboratories but NASA must be certain that the work being done at the university is directly correlated to satisfy NASA's needs. NASA could add further incentives to outside entities by offering access to the shuttle or space station to those conducting the research. This could range from flying a payload specialist to conduct experiments, to offering satellite servicing capabilities to a private contractor.[27]

Although ARP identified many benefits in a strong A&R program for space, they also identified key steps and strategies without which the benefits would not be realizable. NASA must perform the following four steps:

"Step 1 - Provide the advancing technology base.

Step 2 - Conduct early demonstrations (ground and flight) of key new capabilities.

Step 3 - Develop and test prototypes.

Step 4 - Achieve operational implementation."[28]

These steps are only possible through a constant and well planned management process on the part of NASA. NASA must ensure that the Congressional mandate is met.

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[27] Automation & Robotics Panel, pp. 88-89.

[28] Automation & Robotics Panel, p. 116.

To make certain that the necessary milestones and achievements are made NASA must provide:

"* An adequate, stable budget.

* A focus on long range activities and freedom from daily pressures of implementation.

* Goal-setting mechanisms that give a strong voice to both the implementation organization of the space station effort and the A&R technology experts.

* A mixture of in-house and externally funded activities."[29]

The Automation & Robotics Panel (ARP) has suggested that in order to facilitate spinoffs into U.S. industry, NASA must set up mechanisms by which information can be exchanged between NASA and industry such as conferences, networks, and formal data exchange methods. NASA must also provide incentives for new companies and research to become involved with the NASA programs.[30]

Many of the ARP's suggestions have been put into action. For example, due to a wide disparity between available funds for A&R research and the required level suggested by ARP, Congress has taken steps to provide adequate support for A&R in space. Congress augmented the NASA space station budget with provisions for the space station flight telerobotic servicer as a demonstration of commitment to the development of A&R in space despite funding constraints.[31] Hopefully more of these steps will be taken.

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[29] Automation & Robotics Panel, p. 117.

[30] Automation & Robotics Panel.

[31] Reiss, pp. 536-537.

8.3 OFFICE OF TECHNOLOGY ASSESSMENT (OTA) STUDIES

The Office of Technology Assessment (OTA) has also been involved in determining the potential and feasibility of robotics in space. OTA was requested by the Senate Committee on Appropriations, Subcommittee of HUD - Independent Agencies to conduct a March, 1984 exploratory workshop on these issues. The OTA determined that both A&R technology and future space operations would benefit, and the state of the art in A&R could be advanced from an emphasis on A&R in space station R&D.[32]

OTA expressed a serious concern that the goals hoped to be achieved with A&R in space may never be accomplished unless substantial policy changes are made. OTA warned that if the projected level of NASA funding for A&R research does not increase, then no significant advances in the state of the art are likely to result and the future of the space station beyond its initial operating activities could be negatively impacted.[3-133]

The OTA made several observations about the actual implementation of A&R on the space station. Since NASA is interpreting PL 98-371 as meaning that Congress will appropriate funds above those for space station to carry out an A&R program, NASA is reluctant to spend the funds on research other than that related specifically to space station initial operating capability. This makes spinoffs into industrial robotic applications from space R&D very unlikely. If funding is not increased in the NASA Office of Aeronautics and Space Technology A&R research program, the A&R research that will be conducted will have little impact on space station or terrestrial A&R capabilities.[34]

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[32] Office of Technology Assessment (OTA), "Automation and Robotics for the Space Station: Phase B Considerations, An OTA Staff Paper," 1985, p. 1.

[33] OTA, pp. 3-4.

[34] OTA, pp. 4-5.

The technology development program for the space station will assess technologies and evaluate options to influence policies but may not necessarily be able to conduct advanced research in A&R. Certain issues have not yet been addressed such as who is responsible for conducting advanced A&R research, where are the needed resources going to come from, and how will the technologies be spun off into terrestrial applications. Part of the problem points back to PL 98-371 (see Chapter 7) which does not define which systems are to be developed. It does say systems not in use in existing spacecraft, but existing spacecraft use outdated A&R technologies. Report 98-506 makes things a little clearer by stating that technologies should be spun off into terrestrial environments, but still no clear responsibilities or guidelines to accomplish this were mentioned. Additionally these mandates came after initial NASA A&R planning had already begun, making it even more difficult to incorporate them into the research plan. OTA also identified that there is little need for further conceptual studies in A&R, since the potential and the need for A&R R&D for the space station has been determined many times.[3-1] [35]

OTA issued several policy options for Congress that would lead to a greater NASA commitment to A&R resulting in various benefits for the U.S.:

* Congress could stipulate that 10 percent of space station funds within the $8 billion envelope be spent on A&R research (not development). This option would insure advances in A&R that would benefit the U.S. economy at the expense of delaying some A&R capability for initial space station operations.

* Have NASA OAST A&R research program support A&R research at a level equal to ten percent of the total space station budget, but leaving the space station budget intact. This would force OAST to undertake a completely new role to

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[35] OTA, p. 5.

administrate such a huge program. As a result other OAST research programs could suffer.

* Establish a separate A&R research entity that would fund A&R research at the level needed, being separate from any other space station budgetary funds.[36]

OTA also provided several implementation options for the changes in in space A&R research funding policy:

- Establish criteria for advanced A&R and for monitoring research accomplishments.
- Require NASA managers to gain hands-on experience in state of the art industrial automation technology.
- Adopt NASA standards for databases, communications protocols, and interfaces that are based on current industrial and international standards.
- Designate a NASA Center as the lead center for NASA R&D in A&R.
- Create an expert panel to identify critical problems in the space station program where potential A&R solutions could be appropriate.
- Increase the pure research percentage of OAST's A&R funding. The OAST activity could be focused on high-risk technology applicable to both telerobotics and systems autonomy.[37]

OTA has warned that without additional legislation and long-term support from Congress, the ambitious goals of the space station A&R program will never be met. A

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[36] OTA, pp. 6-7.

[37] OTA, pp. 7-8.

clarification of PL 98-371, a molding together of NASA's operational and research efforts, and a dedication from both Congress and NASA would help the meeting of these goals.

8.4 NATIONAL RESEARCH COUNCIL STUDY

The need for U.S. space policy to include provisions for humans to augment their intelligence and manipulative skills through teleoperated systems has also been identified by the National Research Council's Committee on Advanced Space Technology.

The Committee on Advanced Space Technology identified three major reasons why automation and robotics is needed as a critical technology in space: affordability, achievability, and need. However, NASA's use of these technologies has been limited, restricted to deep space missions and certain spacecraft automatic control systems, and not used very often in augmenting the capabilities of humans for in-space manipulation. A lack of investment in the necessary underlying technologies has been cited as the major reason that spaceworthy robotic capabilities do not exist.[38]

The reason NASA has been able to avoid extensive use of remote manipulation is because "for manned missions:

(a) missions have been short and intense, allowing the use of large ground crews for mission control: and

(b) astronauts have historically been "pilots" rather than in-space operators.

For unmanned missions:

(a) spacecraft have been considered "disposable" and were not designed to be serviced on orbit; and

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[38] National Research Council (NRC) Committee on Advanced Space Technology, Space Technology to Meet Future Needs (Washington, D.C.: National Academy Press, 1987), pp. 78-79.

(b) Earth orbiting spacecraft are readily commanded from the ground because of easy communication (relative to deep-space missions)."[39]

The situations described above have quickly become out-dated scenarios as space exploration has been increasingly forced to be more cost effective, and astronauts have become in-space workers needing to perform complex operational tasks in space. These needs for flexibility, productivity, and cost effectiveness will be intensified with the upcoming manned space station and the deployment of in-space serviceable satellites and payloads.[40]

U.S. space policy must incorporate the continued study and use of teleoperation and remote manipulators for future missions for the following reasons that were identified by the NRC Committee on Advanced Space Technology:

"1. Safety of humans in space: Exposure of humans to hazardous environments such as EVA, nuclear and hazardous chemical fuels handling, and high-radiation zones should be minimized.

2. Increased human productivity: Routine and/or hazardous tasks can be automated, and crew time-consuming EVA preparation can be minimized by use of robots.

3. Performance of tasks that are infeasible for humans: Robots can greatly enhance human capabilities for such tasks as moving large structures, capturing spinning satellites, and controlling complex systems.

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[39] NRC, p. 79.

[40] NRC, p. 79.

4. Enabling new missions to other planets: Mobility and manipulation aids for manned missions and automated systems for complex unmanned missions, e.g., Mars rover/sample return, will provide new capabilities."[41]

Space teleoperation will be so different from any Earth-based models that NASA must design and implement their underlying technologies. If NASA does not, they will run the risk of being over-dependent on constrained human productivity in EVA for space operations.[42]

Therefore, although considerable R&D has been conducted for terrestrial uses of robots and manipulators, the space environment poses unique requirements which the NASA R&D program must address. These include:

"* Design will be driven by low-mass requirements that limit power, size, and communication bandwidth (in the case of robotics, mass limitations require mechanization of light, limber manipulators interacting with dynamically active elements such as structures, transportation elements, and free-flying satellites).

* Multipurpose robots will be required for operation in the complex, uncertain, hazardous space environment (relative to factory robots that tend to perform limited, well-defined, repetitive functions) because launching a wide variety of special-purpose robots is too costly and may result in single-point failures, and many space tasks are not predeterminable, thus flexibility and adaptability are essential.

* Very high reliability and safety requirements, especially for manipulators assisting humans in EVA.

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[41] NRC, p. 79.

[42] NRC, p. 81.

* Most important, the man-machine interface is especially critical in manned space missions where each crew member will perform a variety of functions requiring interaction with automated and robotic systems."[43]

Perhaps the most challenging aspect of using robots in space is how to best design and develop a system for interaction between humans and machines. This is a task that lies in the hands of the space community and its technologists and policy makers. The NRC Committee for Advanced Space Technology identified the following key technology areas that need to be addressed to make this interaction effective:

* rapid, precise control of flexible, lightweight manipulator systems
* cooperation between manipulators and between robots
* mobility and maneuverability
* telepresence: human interaction and effective displays
* trainable, model-based systems to be used in unknown environments
* real-time expert systems and predictors
* tools and effectors
* sensing and perception
* advanced in-space computing systems
* maintainability[44]

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[43] NRC, p. 84.

[44] NRC, p. 85.

A visionary and aggressive policy for telerobotics in space would benefit not only the U.S. manned and unmanned space missions, but also applications on the ground. What is needed is a space policy that would support the necessary R&D and mission requirements to further develop the state of the art in space teleoperation. This policy must also increase science or commercial return on investment, reduce operations costs, improve safety and comfort of space operations, and enable many space achievements and operations that would otherwise not be achievable.[45]

Additional funding should be directed toward advances in key enabling technologies and applied research focused on mission needs and applications for remote manipulators. Some technology demonstrations will be needed to validate the systems engineering and systems integration, and the full capabilities including the usability, reliability, safety, and flexibility of human controlled teleoperators in space.[46]

ATAC, ARP, OTA, and NRC have all made in-depth analyses about the potential and policy requirements for the type of automation & robotics program that is need for the U.S. space program and the entire nation. Based on these studies and the other information presented in this thesis, overall policy conclusions and recommendations are presented in Chapter 9.

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[45] NRC, p. 85.

[46] NRC, p. 85.

CHAPTER 9 - POLICY CONCLUSIONS AND RECOMMENDATIONS

This chapter is based on the findings of the previous chapters and how they relate to space remote manipulation policy issues. The following recommendations and conclusions are directed at those parties interested in the use of telemanipulation in space operations. These parties include NASA, Congress, government agencies such as OTA and the National Research Council (NRC), and the many contractors that are developing and determining the capabilities of humans to interact with robotics in space.

Space teleoperation can produce significant benefits.

Many benefits of using telemanipulators have been discussed in this thesis. These benefits include increased productivity, decreased costs, improved reliability, and increased safety. Additionally, significant benefits also exist for the U.S. economy and the stature of U.S. industrial competitiveness through an ambitious space A&R program.

The use of A&R in space is economically feasible.

The productivity and safety advantages of using remote manipulators in space operations translate into considerable cost savings. In addition, the benefits of many of the telemanipulation applications such as satellite servicing can add to additional savings. As discussed earlier in this thesis, the proper use of A&R in space can provide sufficient economic benefits in space and with spinoffs into terrestrial environments to make it a worthwhile program.

The development of A&R in space can provide spinoffs and benefits for terrestrial applications.

Congress and various advisory groups have determined that the development of A&R in space can provide benefits not only for the space program but for the U.S. economy as well. Many terrestrial applications were mentioned in this thesis where A&R from space can be used. This is especially important in key industries such as manufacturing where international competitiveness is a key issue. NASA and Congress should set up mechanisms by which the transfer of technology from government funded R&D can be directly applied to the industrial sector. This could be accomplished by close communication and a pooling of certain resources between the government and the interested industries.

International technology transfer is an important issue.

Congress and other U.S. space policy makers have expressed concern over the transfer of A&R technology between the U.S. and the international space station partners. Although such transfer could hurt U.S. international competitiveness, the U.S. may not want to be overly protectionist. Developing certain technologies for the space station with partners such as Canada, Germany, and Japan could pose advantages for the U.S. program. In addition, the U.S. should not restrict the activities of the partners by too large a degree or run the risk of loosing their cooperation in the program. Therefore space policy makers need to walk a fine line in insuring that technology transfer will not hurt the U.S. position in international competitiveness while also not restricting the operational capabilities of the space station.

Teleoperation can aid in commercial space activities.

Commercialization of space has become a high priority issue for our nation's space program and the future of our venturing into space. Teleoperation will make space operations on the space station more productive, flexible, and less costly. This will lead to a better environment for commercial applications. Specific commercial space activities such as remote satellite servicing, refueling, and maintenance, and the handling of dangerous materials in space manufacturing can be directly aided be remote manipulation. Therefore, the use of remote manipulation, teleoperation, and robotics can facilitate the transition from a totally government funded space program to a more commercially driven program, reaping benefits for both the space program and the U.S. economy.

Existing technology should be utilized whenever possible.

NASA should incorporate the teleoperation research done for terrestrial environments into their program plans. Drawing on existing technologies that have been developed in the nuclear industry, undersea community, academia, and national laboratories could decrease costs and quicken the pace by which space teleoperation develops. This includes using what currently exists for terrestrial applications directly in space operations, or adapting existing technology for specific space tasks.

NASA should take the lead in developing space A&R.

Since there are many differences between the space and terrestrial environments, NASA should be sure to take the lead in developing the unique capabilities needed on the space station. Exploiting existing technologies may be optimal for certain tasks such as inspection and materials handling. But for more advanced tasks such as remote repair missions on spacecraft or altering of experiments remotely, space unique teleoperators will be needed. NASA needs to be the leader in developing these technologies.

Incentives should be established for the participation of industry and academia.

Creating additional university research programs for the development of the space telerobotic systems would be most desirable. Such programs have contributed strongly to these efforts in the past. NASA has seen the utility of involving universities in this research and is currently undergoing a process to expand these efforts. NASA continues to promote these programs and is currently evaluating proposals to set up a NASA center of excellence for automation and robotics at a major university in the near future.

Space station R&D and advanced R&D could be separated.

It may be best to put more concentration on investigating the capabilities and applications of teleoperation in space for space station research, and set up separate research programs which can develop A&R technologies to advance the state of the art with technologies for both advanced space applications and terrestrial applications. This would allow the goals of A&R on the space station to be met by using the space station funding for A&R entirely on specific space station operational applications. Advanced A&R research and development could be done separately, advancing the state of the art without impacting the operational capabilities of the space station.

The investigation of the human/machine interface is critical.

What appears to be needed is more applied research to determine the actual capabilities of robotics, and the abilities of humans to interface productively with A&R in space. The microgravity and unique space environment makes the man/machine interaction for the use of robotics in space much different from that on Earth. Transmission delays and lack of crew time require that the human/machine interface and capabilities of humans to work with manipulators be well understood. The nature of the tasks in space which require flexible operation and specific unique tasks are much different than the usual repetitive robotic tasks performed on Earth. Thus efficient operations are only possible through a thorough understanding of human capabilities to work with telemanipulators in space.

NASA's operational and research efforts should be fused together.

The research and operational sectors of NASA working on A&R should work closely together if the space A&R program is to indeed advance the state of the art. Since the operational requirements for space telemanipulation are so different from those known on Earth, researchers must understand the requirements of the systems and their applications in space. Conversely, operations personnel must understand what the capabilities of present and future systems are in order to effectively plan and direct missions. These efforts would be aided a great deal through close coordination and communication between NASA research and operational divisions.

Space designs should incorporate the use of A&R.

In order to facilitate the effective use of A&R, spacecraft and space flight experiments and equipment should be designed with telemanipulators in mind. This would consist of ensuring that spacecraft were serviceable and that other space flight hardware was controllable with remote manipulators. Thus a standardization of interfaces and protocols would aid in the use of A&R in the space station era.

Technology demonstrations are needed.

Plans to develop and perform various demonstrations of telemanipulation capabilities on Earth and in space are critical. Suggested missions include the use of force feedback on the shuttle remote manipulator system, demonstrations and studies of robotic capabilities in micro-gravity both in EVA and IVA, and the use of telemanipulators in the shuttle bay to test the feasibility of tasks such as the handling of cryogens or the servicing of satellites. One exciting planned experiment is the German ROTEX flight experiment that is scheduled to fly on the D-2 mission. ROTEX will test the capabilities of controlling a robot in micro-gravity remotely, and has become an example of how the various A&R communities can expand their cooperative work into the space station era.[1]

The meaning of Public Law 98-371 must be more clearly stated.

A productive A&R research program for the space station that will also benefit terrestrial environments is only possible if Congress provides additional legislation and guidance to NASA as to what PL 98-371 actually means and sets more explicit funding levels for the next decade and beyond. This will enable NASA to better assess its resources versus its goals and be able to effectively create a plan that will benefit both the space program and international competitiveness.

Currently there is a difference of opinion as to what the "10 percent" in PL 98-371 actually means. The law can be interpreted as meaning 10 percent of all space station costs, or R&D costs, or research only, or development only. Other interpretations are also possible. These questions have left the space community in an uncertain operating mode and have decreased the potentially major impact of this legislation.

The continued support of Congress is needed.

Without the long term dedicated support and cooperation of Congress, the A&R research program for the space station and the country will be one of increasing confusion

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[1] P.P. Chandler, "Automation and Robotics in the Future German Space Program," Space Technology: Industrial and Commercial Applications, Vol. 7, No. 4, 1987, pp. 323-325.

and decreasing benefits for the U.S. Although the space station will use A&R in its operations there is little evidence that it will be able to advance the state of the art in A&R without sufficient Congressional support. This support includes providing long-term funding at the levels suggested by ATAC, ARP, OTA, and NRC. The available resources are limited, and plans must be laid out to use those resources to the fullest extent possible.

Congress has taken steps to help A&R goals of the space station and the industrial sectors become reality. For example allocating funding for the flight telerobotic servicer. However additional steps in legislation, the forming of a long-term robotics in space policy, and meeting required funding levels are needed.

Summary

The use of teleoperators in space can provide substantial benefits in the many areas mentioned in this thesis. However, as outlined above, these benefits are only possible through a committed and well defined space policy for automation and robotics.

APPENDIX A - STATISTICAL METHODOLOGIES

A.1 ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) was selected to analyze the data, because it enables one to detect and analyze the significance of differences not only between means for the same treatment dimension, but also due to the interactions between treatments. The experiments were designed to investigate the performance tradeoffs between treatments of force feedback, tolerance (or task difficulty), viewing distance, and frame rate, while using six experimental subjects and ten trials for each combination of variables for each subject. Thus the power of the analysis of variance technique was necessary to perform a sufficient statistical analysis.

A.2 F-VALUE

Analysis of variance involves calculating an F-ratio for data means, and comparing the calculated F-value to a value in an F distribution table to determine the significance of the difference or variance between the means. The significance will be determined at a certain probability or significance level.

The F-ratio is equal to the mean square value of the variance for each independent variable or interaction between variables (MSV), divided by the mean square value of a corresponding error term (MSE). Analyzing independent variables separately in these experiments corresponds to analyzing differences between frame rates, force feedback conditions, etc., independent of other variables. Interactions are the combined effects of combinations such as frame rate and feedback. Analyzing these combinations is extremely helpful to determine what truly affects subject performance.

The experimental design called for a within-subject design, i.e., each subject performed every task under every experimental condition the same number of times. Therefore the error term used for this analysis was the error due to the inherent differences between the test subjects. This assumes these differences are random, and intersubject differences therefore cannot be tested in the analysis of variance. The mean square values used to calculate the F-value are equal to the corresponding sum of squares divided by the degrees of freedom.[1]

A.3 P-VALUES AND LEVELS OF SIGNIFICANCE

The p-value allows one to test the data against the null hypothesis that the two means are not different. For this thesis a 95 percent confidence level was selected: $p < .05$. Thus if $p < .05$ one can say with reasonably good confidence that the means are different and the associated variable or interaction of variables makes a difference in operator performance. The selection of this level of significance was based on a generally agreed upon rule of thumb in most experimental work: that differences are significant if they occur by chance less than five percent of the time. Further, a difference is generally perceived as highly significant if it occurs by chance once in one hundred tries or $p < .01$.[2]

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[1] William Mendenhall, Richard L. Scheaffer, and Dennis D. Wackerly, Mathematical Statistics with Applications (Boston: Duxbury Press, 1981), pp. 505-517.

[2] Alphonse Chapanis, Research Techniques in Human Engineering (Baltimore: The Johns Hopkins Press, 1959), pp. 125-126.

A.4 SAS PROGRAM

Statistical Analysis System (SAS) was used to perform the analysis of variance. Dr. Beverly Chew, a consultant with MIT Information Services assisted by writing the necessary code (see next page). The performance data was structured by assigning each data point six different descriptors:

1) subject number (1-6)
2) frame rate (30, 3, or 5 frames /sec) for video viewing or distance (4, 8, or 12 feet) for direct viewing
3) tolerance level (1, .5, or .25 inches)
4) force feedback condition (with or without)
5) direction (going to the left or going to the right)
6) repetition for right and left direction (1-5 for each direction for a total of 10 trials).

One difficulty in the analysis was incurred when dealing with the number of trials as a variable. The optimal way to treat the number of trials would be to include them as a random variable. Unfortunately the resources to do this were not available. However, the trials were included in the analysis as a fixed variable.

```
FILE: MIKEBIG  SAS      A                   VM/SP CONVERSATIONAL MONITOR SYSTEM

CMS FILEDEF DISKIN DISK VIDEO TXT2 A;
DATA MIKE.VIDEO2;
INFILE DISKIN;
INPUT SUBJECT FRAME FDB TOL DIR REP T;
TITLE "MECHANICAL ENGINEERING: VIDEO DATA";

PROC SORT DATA=MIKE.VIDEO2;
BY SUBJECT FRAME FDB TOL DIR REP;

PROC PRINT DATA=MIKE.VIDEO2;

PROC SUMMARY;
CLASS SUBJECT FRAME FDB TOL DIR;
VAR T;
OUTPUT OUT=MIKE.SUMV N=N MEAN=MEAN STD=STD STDERR=STDERR MIN=MIN MAX=MAX;

PROC PRINT DATA=MIKE.SUMV;
```

```
FILE: ANOVA    SAS      A                   VM/SP CONVERSATIONAL MONITOR SYSTEM

PROC ANOVA DATA=MIKE.VIDEO2;
CLASS SUBJECT FRAME FDB TOL DIR REP;
MODEL T = SUBJECT¦FRAME¦FDB¦TOL¦DIR¦REP/SS4:
RANDOM SUBJECT;
MEANS FRAME / SNK E=SUBJECT•FRAME ETYPE=4 HTYPE=4;
MEANS TOL / SNK E=SUBJECT•TOL ETYPE=4 HTYPE=4;
```

A.5 POST-HOC TESTS

The analysis of variance tables that were output from SAS provide an initial indication of what means and conditions were significantly different from others, for example frame rate did or did not make a difference. However, to explore deeper and draw conclusions as to what frame rates are significantly different from what other frame rates, post-hoc tests are necessary. The post-hoc test used was the Newman-Keuls test.[3]

The Newman-Keuls procedure calculates a critical range for each pair of samples with the following formula:

$$CR = q(ms/n)^{.5}$$

where: ms = the residual mean square from the ANOVA table, which is the ANOVA sum of the squares for the error term divided by the degrees of freedom

n = the sample size

q = the studentized range statistic for r samples, where r = 2 if the ordered samples are adjacent (ex-3 frames/sec and 5 frames/sec) and r=3 if there is a sample between the two samples being compared (ex-3 frames/sec and 30 frames/sec).

The q-value is determined by using a Newman-Keuls multiple comparison factors table by specifying r, df, the degrees of freedom for ms, and the significance level chosen for the tests (in this thesis the significance level equals .05). For interactions, the mean square used is the largest one out of the mean square for each variable individually and all possible combinations.

If the difference between the sample means is greater than the critical range, one can reject the null hypothesis (the means are not significantly different = the null hypothesis).

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[3] Francis J. Wall, Statistical Data Analysis Handbook, (New York: McGraw-Hill, 1986), pp. 5.10-5.12.

Thus the data samples can be considered to be significantly different. If the difference is less than the critical range than the null hypothesis is accepted and the means are not considered to be significantly different.

APPENDIX B - EXPERIMENTAL DATA

TABLE B.1 - MEAN TASK TIMES FOR VIDEO VIEWING PERFORMANCE

INDEX OF DIFFICULTY (BITS/TASK)	FORCE FEEDBACK (YES or NO)	FRAME RATE (FRAMES/SEC)	MEAN TASK TIME (SECONDS)
4	YES	30	1.73
5	YES	30	1.96
6	YES	30	2.45
4	NO	30	2.66
5	NO	30	2.88
6	NO	30	3.69
4	YES	5	2.83
5	YES	5	2.92
6	YES	5	3.41
4	NO	5	4.91
5	NO	5	5.48
6	NO	5	7.32
4	YES	3	3.28
5	YES	3	3.87
6	YES	3	4.31
4	NO	3	5.88
5	NO	3	6.61
6	NO	3	8.21

TABLE B.2 - MEAN TASK TIMES FOR DIRECT VIEWING PERFORMANCE

INDEX OF DIFFICULTY (BITS/TASK)	FORCE FEEDBACK (YES or NO)	VIEWING DISTANCE (FEET)	MEAN TASK TIME (SECONDS)
4	YES	4	1.23
5	YES	4	1.53
6	YES	4	1.74
4	NO	4	1.88
5	NO	4	2.20
6	NO	4	2.92
4	YES	8	1.45
5	YES	8	1.71
6	YES	8	2.21
4	NO	8	2.45
5	NO	8	2.60
6	NO	8	3.19
4	YES	12	1.55
5	YES	12	1.74
6	YES	12	2.26
4	NO	12	2.78
5	NO	12	3.10
6	NO	12	4.10

TABLE B.3 - SUBJECT #1 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	1.2	1.8	1.49	1.84	1.87	2.88
	2.12	1.41	1.97	1.68	1.98	2.13
	1.34	1.39	1.98	2.08	2.61	10.74
	3.04	1.93	1.27	3.05	2.01	2.5
	0.96	1.92	1.95	2.42	1.93	4.02
	0.84	1.39	1.4	1.16	2.23	2.6
	1.17	2.31	1.52	1.71	2.84	3.97
	1.56	1.46	1.82	2.1	2.07	1.97
	1.48	1.97	1.69	1.35	2.74	1.37
	1.44	1.78	1.87	2.65	2.03	1.34
MEANS:	1.52	1.74	1.70	2.00	2.23	3.35
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	2.25	2.25	2.01	2.11	5.86	3.65
	2.2	3.21	2.07	5.05	2.53	16.44
	2.21	1.85	1.92	4.66	3.36	5.02
	3.1	2.94	4.51	6.33	4.11	7.18
	1.2	1.87	5.87	4.57	4.1	4.45
	1.47	2.77	2.99	3.65	2.62	8.84
	2.76	2.61	2.21	4.83	3.5	8.71
	3.88	.23	2.13	3.49	10.51	15.8
	3.23	2.25	2.08	4.67	3.22	9.12
	2.62	1.56	2.81	4.32	6.97	9.9
MEANS:	2.492	2.354	2.86	4.368	4.678	8.911
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	2.72	2.25	2.32	3.22	5.48	5.7
	1.06	1.4	2.25	11.75	4.57	7.73
	2.08	2.13	2.71	4.14	5.47	5.74
	2.04	3.5	2.6	7.45	7.36	11.15
	2.15	2.12	2.68	4.68	5.89	6.33
	2.1	1.41	3.47	4.06	4.64	8.49
	3.22	2.09	2.04	4.29	5.14	6.69
	1.26	2.38	2.1	9.23	5.09	11.47
	2	1.95	2.05	6.48	6.04	11.02
	1.77	1.27	1.98	10.56	4.3	6.69
MEANS:	2.04	2.05	2.42	6.586	5.398	8.101

TABLE B.4 - SUBJECT #2 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	3.03	3.15	4.55	3.66	2.55	3.38
	1.6	3.91	3.71	5.98	3.26	3.41
	2.21	1.67	1.62	3.51	4.06	3.52
	2.28	1.54	2.97	3.81	2.78	5.24
	1,63	1.41	4.21	6.65	3.31	4.62
	1.59	3.01	2.7	3.24	3.15	5.19
	1.48	1.28	2.19	2.82	2.8	4.1
	2.32	2.52	1.78	2.73	3.2	5.24
	2.02	1.88	2.3	4.8	2.5	2.39
	1.67	3.19	3.07	2.58	5.73	5.9
MEANS:						
	1.983	2.356	2.91	3.978	3.334	4.301
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	3.53	4.01	2.76	5.17	8.14	8.24
	3.33	2.25	4.91	4.71	8.65	10.31
	4.68	4.17	4.68	5.71	4.86	15.12
	3.77	4.21	3.46	4.44	5.72	9.79
	3.46	5.21	3.62	5.03	4.49	18.3
	2.73	3.52	2.53	4.58	8.24	7.66
	3.22	4.22	6.05	7.01	5.29	11.3
	3.61	4.11	3.5	5.87	5.13	6.64
	3.88	4.16	3.12	4.72	4.96	10.68
	1.82	1.912	2.99	6.69	5.23	7.13
MEANS:						
	3.403	3.7772	3.762	5.393	6.071	10.523
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	3.33	4.59	4.75	5.94	5.31	6.7
	6	3.05	3.6	4.33	7.54	3.56
	2.73	4.82	5.32	8.76	7.88	12.63
	5.51	4.89	6.32	5.88	4.35	4.55
	3.85	4.35	7.29	4.18	6.7	4.73
	5.17	4.5	5.9	4.69	4.11	4.5
	2.78	5.1	7.11	4	6.58	5.08
	4.21	2.55	5.01	7.89	4.15	7.84
	3.81	4.64	3.99	4.79	4.59	8.92
	4.3	4.17	4.89	6.1	3.52	9.6
MEANS:						
	4.169	4.266	5.418	5.656	5.473	6.812

TABLE B.5 - SUBJECT #3 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	1.16	1.54	2.14	1.99	3.62	3.71
	1.22	2.06	9.05	2.6	2.5	3.97
	2.16	2.02	2.83	1.47	2.68	1.87
	2.09	2.08	2.07	1.7	3.07	3.44
	1.44	2.45	2.58	1.15	1.96	2.9
	1.63	1.3	1.76	3.66	2.54	2.51
	1.96	1.45	2.38	3.71	2.01	3.45
	0.98	2.79	1.49	1.32	2.6	2.45
	1.73	2.04	1.67	1.47	1.66	3.4
	0.99	1.51	2.08	1.11	1.81	2.83
MEANS:						
	1.536	1.924	2.805	2.018	2.445	3.055
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	3.01	2.71	3.89	3.55	9.65	5.49
	4.21	4.3	3.37	7.52	8.8	6.92
	2.92	3.2	4.01	12.75	4.51	4.21
	3.09	3.28	1.68	2.17	3.27	8.4
	1.88	1.85	2.32	7.2	5.82	6.66
	2.12	1.72	2.67	7.86	3.02	5.4
	2.78	3.56	3.54	8.13	5.02	6.22
	2.19	1.57	3.35	2.37	9.87	4
	1.5	2	2.75	5.38	9.65	5.88
	2.25	2.22	5.33	5.33	6.99	4.06
MEANS:						
	2.595	2.641	3.291	6.226	6.66	5.733
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	3.49	4.46	3.26	8.14	2.94	10.89
	3.25	6.02	9.63	3.85	6.09	9.64
	2.47	2.55	5.24	7.03	11.83	12.44
	2.6	5.46	2.94	6.19	5.23	12.88
	1.57	2.22	3.97	8.86	6.39	10.34
	2.68	3.48	3.23	3.48	19.12	4.09
	1.61	1.89	2.2	10.67	7.68	5.95
	2.17	4.78	3.52	6.09	5.67	5.03
	2.26	2.19	2.86	14.09	7.5	4.99
	2.5	6.96	4.08	3.55	5.76	8.26
MEANS:						
	2.46	4.001	4.093	7.195	7.821	8.451

TABLE B.6 - SUBJECT #4 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	3.11	2.52	2.35	2.46	3.18	2.56
	1.87	1.31	1.6	3.52	3.84	2.53
	1.17	2.32	1.66	2.66	1.85	2.23
	2.43	1.64	1.7	3.39	3.97	4.3
	0.86	1.02	1.35	2.09	2.05	6.22
	1.72	1.41	1.5	1.85	2.18	2.95
	1.54	0.95	1.58	1.73	2.33	6.92
	2.26	1.2	1.74	4.17	2.86	3.27
	1.36	1.26	1.34	5.61	1.62	3.56
	0.96	1.48	1.62	3.29	4.87	2.57
MEANS:						
	1.73	1.51	1.64	3.08	2.88	3.71
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	2.12	3.9	4.21	7.9	3.59	12.03
	2.75	1.8	2.84	7.23	4.64	3.8
	2.87	1.62	2.78	6.58	5.3	6.48
	3.4	1.68	1.86	5.54	4.09	3.29
	2.82	3.05	7.33	3.55	5.86	4.18
	1.25	2.78	1.83	3.17	2.87	3.2
	1.46	1.89	6.5	5.39	2.93	2.41
	2.57	1.69	2.41	4.91	8.74	7.57
	1.43	1.9	2.2	3.43	3.31	4.38
	2.14	2.25	3.32	2.94	3.4	3.5
MEANS:						
	2.28	2.26	3.53	5.06	4.47	5.08
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	7.32	5.26	5.59	9.1	10.63	7.91
	2.52	3.07	3.18	6.6	8.75	8.42
	2.65	3.06	3.61	4.68	12.93	7.29
	2.25	4.92	3.59	6.44	4.74	3.96
	2.35	3.41	3.07	5.08	5.9	8.19
	1.95	3.8	5.96	4.8	5.91	8.31
	2.47	2.63	3.2	6.91	5.4	7.58
	3.14	2.9	3.6	4.51	13.46	4.83
	6.29	2.66	2.3	3.85	3.61	4.82
	3.85	2.9	4.15	8.99	8.27	6.01
MEANS:						
	3.48	3.46	3.83	6.10	7.96	6.73

TABLE B.7 - SUBJECT #5 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	2.99	2.13	2.93	2.24	2.21	7.53
	1.86	5.37	4.17	2.42	2.42	2.68
	1.55	1.95	4.49	2.65	3	5.21
	1.95	2.98	3.38	2.34	2.45	3
	1.41	1.64	3.4	1.75	2.22	1.96
	1.99	1.42	1.35	1.95	2.53	4.29
	1.86	1.41	2.48	3.26	5.83	5.21
	1.99	1.38	3.64	2.59	4.68	5.6
	1.35	2.38	2.54	2.68	3.57	3.03
	2.46	2.1	3.54	2.18	4.22	2.52
MEANS:						
	1.94	2.28	3.19	2.41	3.31	4.10
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	3.67	6.66	4.99	3.75	6.59	4.95
	4.99	3.55	4.63	6.32	6.52	5.56
	3.06	4.78	3.69	2.98	5.74	10.21
	4.51	3.24	4.93	2.53	4.13	6.11
	3.21	4.06	3.99	8.52	4.92	3.4
	2.55	4.39	3.62	3.53	4.94	15.18
	4.78	3.05	3.06	4.46	6.8	5.4
	2.21	3.59	4.45	2.98	7.56	15.31
	3.49	2.89	3.65	3.34	4.73	3.57
	5.12	3.78	3.02	2.87	3.7	8.48
MEANS:						
	3.76	4.00	4.00	4.13	5.56	7.82
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	5.32	4.13	5.26	2.88	5.09	10.74
	2.97	3.8	6.1	6.25	7.69	25.9
	2.95	3.78	5.05	5.12	8.38	6.89
	2.63	5.85	3.68	6.99	8.15	19.81
	5.53	3.82	8.86	3.61	11.93	10.38
	3.51	4.1	5.41	7.47	4.28	5.75
	4.87	6.54	3.4	4.26	4.46	4.99
	3.62	7.15	4.75	3.68	6.07	23.47
	4.88	5.48	7.07	3.18	5.46	4.09
	3.59	6.47	6.88	3.87	4.26	9.32
MEANS:						
	3.99	5.11	5.65	4.73	6.58	12.13

TABLE B.8 - SUBJECT #6 - VIDEO VIEWING PERFORMANCE DATA

FFB = force feedback, FPS = frames/sec, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	30 FPS, FFB			30 FPS, NO FFB		
Task times for ten trials:						
	2.69	2.56	3.11	2.58	3.09	3.53
	1.64	1.99	2.53	2.12	2.68	3.97
	1.51	2.26	2.3	2.92	2.99	2.55
	1.07	1.32	2.15	2.56	5.66	4.15
	2.95	1.83	2.97	2.39	3.11	3.09
	1.45	1.94	1.72	3.59	2.23	3.6
	1.73	2.21	2.65	2	2.96	4.29
	1.26	2.12	2.14	1.68	2.4	4.53
	1.38	1.63	2.6	2.74	2.36	4.42
	1.34	1.81	2.57	1.97	3.44	2.1
MEANS:						
	1.70	1.97	2.47	2.46	3.09	3.62
	5 FPS, FFB			5 FPS, NO FFB		
Task times for ten trials:						
	2.45	2.72	4.62	3.12	2.95	6.55
	2.54	2.32	3.43	8.75	3.2	6.39
	2.21	3.12	2.29	2.96	5.25	4.44
	1.78	3.12	2.48	7.16	9.43	4.07
	3.74	1.8	2.92	2.31	3.91	6.13
	2.76	2.67	3.26	3.6	6.91	3.34
	1.74	3.13	3.96	2.72	2.22	7.38
	1.76	1.9	1.98	4.2	3.85	6.58
	2.93	2.37	3.29	4.91	12.45	7.62
	2.65	2.03	2.15	2.79	4.19	5.69
MEANS:						
	2.46	2.52	3.04	4.25	5.44	5.82
	3 FPS, FFB			3 FPS, NO FFB		
Task times for ten trials:						
	4.59	2.9	4.66	4.44	5.19	5.21
	2.8	3.37	8.02	4.43	3.83	6.74
	3.14	2.23	4.61	3.82	3.73	8.68
	4.7	4.18	3.37	4.76	8.46	5.13
	3.56	2.46	3.8	5.11	10.86	16.58
	3.16	7.29	4.09	3.95	12.18	4.94
	4.9	10.17	5.76	5.5	3.05	5.06
	2.28	5.62	3.89	5.84	4.87	7.83
	2.87	2.7	3.27	6.9	5.39	5.11
	3.61	2.12	3.03	5.65	6.53	5.21
MEANS:						
	3.56	4.30	4.45	5.04	6.41	7.05

TABLE B.9 - SUBJECT #1 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	1.36	1.87	2.27	1.6	2.36	1.62
	1.61	1.31	1.23	2.43	1.86	1.66
	1.07	1.75	1.94	1.35	1.81	2.79
	1.87	1.64	1.92	2.82	2.6	3.01
	0.94	1.2	1.46	1.48	2.45	1.84
	1.62	1.7	1.48	1.2	1.61	2.07
	1.21	2.22	1.9	1.55	2.15	2.85
	0.95	1.46	1.2	1.69	2.67	2.33
	1.86	1.21	1.34	1.34	1.75	4.95
	1.69	1.9	1.3	2.16	1.62	3
MEANS:						
	1.42	1.63	1.60	1.76	2.09	2.61
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	1.56	1.97	2.2	1.53	2.55	3.6
	1.31	1.9	1.97	3	2.71	1.7
	1.35	1.63	2.06	2.22	1.67	3.09
	1.49	1.86	2.65	1.56	3.26	1.6
	1.39	2.11	2.64	1.65	3.88	2.61
	1.22	1.53	1.4	5.23	1.96	2.32
	1.87	2	2.33	1.82	2.17	2.74
	1.94	1.29	1.94	5.7	2.36	2.57
	1.88	2.31	1.95	5.36	1.56	5.38
	2.37	1.87	2.27	1.77	3.21	1.75
MEANS:						
	1.64	1.85	2.14	3.03	2.53	2.74
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	1.31	1.49	2.49	4.39	1.36	3.25
	1.3	1.88	1.97	3.59	1.54	2.77
	1.09	1.53	1.97	2.91	2.83	3.36
	1.88	1.34	1.74	1.43	2.56	2.27
	1.06	1.69	1.79	3.28	3.22	1.3
	1.2	1.57	1.76	6.59	1.59	2.64
	1.13	0.99	2.27	1.34	3.57	7.28
	1.91	0.97	1.01	6.29	2.17	4.32
	1.16	1.51	1.71	1.64	2.52	2.48
	1.14	1.64	1.71	4.07	6.72	11.55
MEANS:						
	1.32	1.46	1.84	3.55	2.81	4.12

TABLE B.10 - SUBJECT #2 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	2.02	1.95	1.57	1.92	2.54	4.42
	1.75	1.22	3.57	1.41	2.51	2.27
	1.6	1.44	1.14	1.58	1.69	2.47
	1.26	1.53	2.02	1.49	1.43	4.82
	1.22	1.8	2.18	1.96	2.05	2.2
	1.19	1.38	2.23	1.76	1.26	2.37
	1.32	2.28	2.08	1.72	1.9	2.49
	1.15	2.58	2	1.49	3.74	1.7
	1.14	1.53	2.16	3.49	5.52	1.53
	0.98	1.39	2.07	1.49	2.02	2.77
MEANS:						
	1.36	1.71	2.10	1.83	2.47	2.70
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	2.15	1.99	3.11	3.64	2.52	5.05
	1.62	2.88	2.92	2.59	1.61	2.78
	2.16	1.53	2.5	3.19	2.47	3.47
	1.32	2.03	3.11	2.53	5.08	3.24
	1.26	2.47	3.25	4.08	5.17	3.59
	1.46	1	2.64	1.96	2.68	2.68
	1.25	1.05	2.99	1.68	2.64	2.79
	1.82	1.88	2.49	3.2	2.53	3.1
	1.4	1.68	1.93	3.85	4.77	2.6
	1.19	1.89	3.75	2.47	2.79	2.8
MEANS:						
	1.56	1.84	2.87	2.92	3.23	3.21
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	2.71	1.43	1.87	2.7	3.25	4.41
	2.35	1.58	4.49	2.75	3.24	5.54
	3.18	2.23	4.09	2.45	4.71	10.49
	1.43	2.1	2.12	2.58	3.45	3.21
	1.02	3.07	2.57	2.59	3.61	3.93
	2.48	1.78	1.61	2.83	2.81	4.2
	1.82	1.49	2.08	7.38	3.61	2.42
	1.54	1.51	2.24	4.06	2.8	4.23
	2.2	1.75	2.06	3.49	5.66	3.65
	1.51	1.33	2.69	3.44	2.16	3.92
MEANS:						
	2.02	1.83	2.58	3.43	3.53	4.6

TABLE B.11 - SUBJECT #3 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	1.09	1.38	1.87	1.67	2	1.98
	1.04	2.31	1.73	1.52	3.1	1.77
	0.92	1.39	1.96	2.11	1.69	2.7
	1.38	0.97	1.9	2.05	3.61	5.76
	0.87	1.8	1.79	1.66	5.05	4.1
	1.4	1.58	1.64	2.75	1.49	3.99
	1.48	1.15	1.83	1.98	1.9	2.4
	0.74	1.04	2.38	1.51	3.86	2.34
	1.01	1.17	2.41	2.65	1.96	3.2
	0.87	1.51	0.81	1.11	2.27	1.53
MEANS:						
	1.08	1.43	1.83	1.90	2.69	2.98
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	1.17	1.37	4.05	2.34	2.62	4.55
	1.09	1.62	1.27	2.01	2.1	2.37
	1.04	2.38	2.33	2.47	2.78	5.56
	0.77	1.67	2.54	1.96	1.69	2.16
	1.39	1.11	1.18	2.41	6.27	7.53
	1.29	1.72	1.81	2.09	2.72	2.7
	1.25	1.65	1.79	2.12	2.73	2.63
	1.46	0.91	3.01	3.43	1.75	4.79
	0.89	2.2	1.64	3.39	2.42	3.9
	1.33	1.47	1.91	3.44	5.16	1.87
MEANS:						
	1.17	1.61	2.15	2.57	3.02	3.81
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	1.65	2.94	1.81	2.51	2.57	8.67
	1.52	1.47	2.35	2.28	2.91	9.44
	1.94	2.03	1.81	2.71	2.69	3.74
	1.25	1.96	1.75	2.08	2.25	3.4
	0.99	3.02	1.49	2.99	2.29	2.57
	1.5	2.2	2.68	2.69	5.53	2.86
	0.95	1.3	1.41	1.85	3.06	3.49
	1.12	2.14	2.27	5.13	5.37	8.64
	1.63	2.02	1.76	2.5	4.01	2.41
	1.07	1.3	2.11	2.04	4.61	2.87
MEANS:						
	1.36	2.04	1.94	2.68	3.53	4.81

TABLE B.12 - SUBJECT #4 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	1.37	1.17	1.22	1.35	1.38	1.26
	0.97	0.96	2.76	1.1	2.82	1.69
	1.59	1.23	1.11	1.56	1.13	1.89
	0.98	1.26	1.85	1.06	1.65	0.94
	0.77	1.56	1.14	1.3	2.23	2.06
	0.86	1.29	1.24	1	1.09	0.88
	1.01	1.15	2	2.5	0.97	1.54
	0.82	1.21	1.35	1.78	1.01	2.02
	0.92	0.91	1.03	2.62	0.89	3.09
	1.44	0.97	1.31	1.34	1.09	1.85
MEANS:						
	1.07	1.17	1.50	1.56	1.43	1.72
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	1.1	1.16	1.6	1.38	1.18	1.41
	1.07	1	2.22	1.4	1.37	2.24
	0.97	1.17	2.08	1.38	2.58	2.21
	0.75	1.95	1.73	2.16	1.31	3.77
	0.88	1.02	1.84	2.16	1.64	1.77
	1	0.93	1.35	1.26	1.96	6.49
	1.74	1.5	1.06	1.29	1.31	1.68
	2.12	1.54	1.48	1.28	1.88	4.35
	1.03	1.63	1.17	1.56	1.27	1.73
	1.32	0.97	1.59	1.88	2.37	1.6
MEANS:						
	1.20	1.29	1.61	1.58	1.69	2.73
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	1.63	1.42	2.33	1.82	2.44	1.87
	1.53	3.38	2.62	2.37	1.76	3.05
	1.31	1.35	1.05	1.4	1.76	1.86
	1.94	1.09	1.44	1.59	1.39	3.57
	1.25	1.06	1.44	1.26	2.21	3.41
	0.98	1.45	1.64	1.6	2	4.34
	0.95	1.64	1.01	1.87	1.82	3.73
	1.07	1.05	2.2	1.64	3.08	3.59
	1.32	1.74	1.34	1.55	1.68	3.01
	0.82	1.3	1.43	2.04	1.91	1.94
MEANS:						
	1.28	1.55	1.65	1.71	2.01	3.04

TABLE B.13 - SUBJECT #5 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	1.54	1.6	2.26	1.83	2.58	4.55
	1.57	2.34	1.54	1.85	2.5	4.12
	1.43	2.31	1.86	3.2	1.91	9.95
	1.31	1.16	2.18	3.55	2.36	3.51
	1.19	1.85	1.69	2.01	2.69	7.4
	1.18	1.69	1.83	2.23	2.15	4.7
	1.22	1.68	1.64	2.16	3.01	4.29
	1.37	1.51	2.12	2.65	2.78	6.1
	1.86	2.08	1.62	2.53	3.49	4.77
	1.85	1.4	1.53	2.11	2.81	3.22
MEANS:						
	1.45	1.76	1.83	2.41	2.63	5.27
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	1.24	1.72	1.97	2.43	2.61	6.33
	2.07	2.03	1.58	3.95	4.36	4.02
	1.56	2.07	2.76	3.12	2.49	4
	1.64	2.14	1.65	2.44	4.9	3.56
	2.27	3.11	2.53	4.28	2.94	4.7
	1.5	1.52	5.61	2.73	3.25	3.15
	1.57	2.13	3.72	2.81	2.41	4.33
	1.69	1.65	2.22	2.22	3.01	3.04
	3.13	2.24	1.98	2.22	2.05	4.45
	1.81	2.37	2.22	2.43	4.06	3.53
MEANS:						
	1.85	2.10	2.62	2.86	3.21	4.11
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	1.91	1.79	2.55	2.17	5.66	3.49
	2.31	2.02	5.55	2.44	4.42	5.26
	1.64	2	2.36	2.94	4.4	3.45
	1.68	2.43	2.84	2.81	3.29	3.15
	1.61	1.77	3.08	4.95	2.1	3.6
	2.78	2.41	4.03	2.95	7.49	9.94
	1.76	2.16	4.21	2.6	3.25	5.52
	2.36	1.99	2.38	2.89	2.72	3.02
	1.68	2.34	2.44	3.71	3.02	6.76
	2.87	2.22	4.01	2.87	2.93	6.03
MEANS:						
	2.06	2.11	3.35	3.03	3.93	5.02

TABLE B.14 - SUBJECT #6 - DIRECT VIEWING PERFORMANCE DATA

FFB = force feedback, Id = index of difficulty (bits/task)
Task times are in seconds.

Id:	4	5	6	4	5	6
	4 FEET, FFB			4 FEET, NO FFB		
Task times for ten trials:						
	0.86	1.85	2.1	1.67	2.76	3.84
	1.19	1.98	1.76	2.02	2.41	2.18
	0.96	1.18	1.53	1.41	1.66	1.91
	0.91	1.26	1.14	2.06	2.09	1.51
	0.77	0.98	1.28	1.32	1.49	1.66
	1.11	2.09	1.44	1.36	1.42	2.16
	1.1	1.55	1.57	2.87	1.64	2.39
	0.95	1.43	1.21	1.26	2.14	2.01
	0.99	1.31	1.86	1.42	1.58	2.3
	0.87	1.14	1.66	2.88	1.6	2.41
MEANS:						
	0.97	1.48	1.56	1.83	1.88	2.24
	8 FEET, FFB			8 FEET, NO FFB		
Task times for ten trials:						
	1.37	1.21	1.37	1.9	1.92	3.58
	1.91	1.78	1.72	1.45	1.94	3.76
	1.19	1.44	1.89	2.02	1.51	2.26
	1.08	2.12	1.79	1.58	2.25	1.93
	0.98	1.82	1.93	1.98	1.72	1.97
	1.51	1.26	2.08	1.34	2.66	2.66
	1.35	1.48	1.74	2.24	1.78	2.64
	1.2	1.46	1.93	2.51	1.64	2.39
	1.03	1.46	2.29	1.19	1.99	1.67
	1.08	1.62	1.69	1.12	1.61	2.44
MEANS:						
	1.27	1.57	1.84	1.73	1.90	2.53
	12 FEET, FFB			12 FEET, NO FFB		
Task times for ten trials:						
	1.23	1.55	4.33	3.14	4.77	4.27
	1.42	1.16	1.63	2.84	3.13	3.13
	1.17	1.21	1.8	1.95	3.18	3
	1.33	1.57	2.58	1.33	1.65	2.18
	1.38	2.01	2.03	3.84	2.71	1.54
	0.96	1.33	2.43	1.67	2.95	2.18
	1.08	1.69	2.08	2.34	1.86	2.28
	1.31	1.31	1.68	1.82	2.45	6.58
	1.51	1.31	1.57	1.94	2.06	2.3
	1.01	1.57	2.04	1.59	3.26	2.36
MEANS:						
	1.24	1.47	2.22	2.25	2.80	2.98

APPENDIX C - ASTRONAUT WHITE PAPER ON AUTOMATION AND ROBOTICS

Source: NASA Advanced Technogoly Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 1, NASA TM 87772, April - September, 1985, pp. 39-41.

U S Government
MEMORANDUM

Lyndon B Johnson Space Center NASA

REFER TO CB-85-027
DATE APR 1 1985
INITIATOR CB/McCandless/Parker:td:12/20/84
ENC. 1

TO PA/Manager, Space Station Program
CC See list below

FROM CA/Director, Flight Crew Operations
SIGNATURE Original signed by George W. S. Abbey
George W. S. Abbey

SUBJ: Space Station Crew White Paper on Automation and Robotics

During the past year, Capt. Bruce McCandless and Dr. Robert Parker, representing the Flight Crew Operations Directorate, participated in your Space Station RFP preparation and subsequent evaluation activities. As members of your Operations group, they were involved in a number of definition activities including the potential use of automation and robotics in station operations. As part of these activities, they were requested by your Operations group to prepare a crew position paper on use of automation and robotics. That paper is included in this memorandum.

As technology progresses, the scope of tasks amenable to automation or to accomplishment by robot means increases. In less than a quarter of a century we have evolved from the computerless, hardwired, Mercury spacecraft to a fly-by-wire, multi-computer controlled, reusable spacecraft that is dependent upon uninterrupted, accurate, high speed digital computations for flight control and aerodynamic stability as well. At this stage of evolution of the Space Station Program it is appropriate to attempt to assess the role that these technologies should be assigned in the developmental stages so as to result in the most effective utilization of crew resources. It is assumed that at least the current level of automation of guidance and control systems will be incorporated into the station design.

In order to be realistically available to support the 1992 Initial Operational Capability (IOC) date, commercial prototype or operational laboratory systems must be available by the end of FY86. This is not to imply that later blooming technology should be barred from the Space Station; only that we must be able to get along at IOC with whatever exists in tangible, useful form elsewhere by the end of FY86. Premature implementation of automation and robotics will only lead to unnecessary complexity, cost, and degradation of Space Station performance.

The following are submitted as working groundrules.

a. Automation and/or roboticization of Space Station systems should be based on cost-effective increases in productivity or on meeting systems operational requirements rather than solely for the sake of advancing the state of such technologies. "Spin-off" technological benefits will be an inherent product of this effort.

b. Target areas should be those that offer the greatest potential for relieving the crew of time-consuming, time-critical, repetitious, physically taxing, hazardous, non-creative, or boring activities. Supervisory decision-making control should normally be reserved to human operators, either onboard or on the ground. Efforts to automate supervisory decision functions must always provide human override capability.

c. Automated systems must be capable of being reconfigured and reprogrammed by the crew. Consequently, the software packages must be as independent as possible so as to not interfere with the safe operation of the station while work on an individual system is under way.

d. Currently budgeted allocations of crew time to tasks such as systems management, replanning, training and unscheduled activities are based on years of accumulated spaceflight experience. These values should be retained for IOC planning until such time as sufficient experience is gained with expert systems in a flight environment to warrant reductions. Increased time available for direct customer support may eventually be realized as such systems are phased in and mature, but should not be anticipated for IOC planning.

e. All essential functions performed by automated or robotic means must have effective means available to the crew for the override, troubleshooting, and functional backup of the subject system.

f. Normal crew interaction with an automated or robotic system must be maintained at a minimal but sufficiently high level that operator proficiency and familiarity with its features are not lost over time, with the loss only being recognized when the system quits or suddenly exhibits unfamiliar or anomalous behavior.

g. In order to develop credibility and maturity, Shuttle technology demonstration flights of essential automation/robotics elements should be scheduled and funded ASAP.

h. Monitoring and alarm means (e.g., caution & warning systems) should be kept independent of control means so as to avoid common failure modes. Additionally, while an "expert system" for failure diagnosis might profitably be incorporated into the caution and warning system, and could display appropriate schematics and the rules leading up to its diagnosis, the basic functions of a C & W system must be readily available even if the expert system itself should prove troublesome.

i. Early emphasis should be placed on achieving originally intended performance from existing automated systems that do not function satisfactorily. A specific example of this is the Orbiter cabin temperature controller; if it is not manually pinned into position, it drives to one limit or the other. Only on the thirteenth flight of the Orbiter (STS 41-G) has this system been made to function in a proportional, but still uncalibrated, mode.

j. On-orbit maintenance operations should not be reduced to rote repetition activities via a system such as a heads-up display based automated video maintenance information system. Such an approach would lead to crew indifference and ignorance due to concentration on manipulative "nuts and bolts" tasks at the expense of intellectual involvement and comprehension.

k. Robotic systems must include "teaching pendants" or similar means for on-orbit "re-education" of the devices or development of new tasks. An effective means of collision avoidance and contact sensing must be provided.

A number of specific tasks or areas considered particularly appropriate for automation and/or roboticization by the flight crew are listed in the Appendix to this "white paper".

Several of the recommended tasks or areas in the Appendix were proposed in the early Space Shuttle designs such as onboard automated flight planning, automated systems management, and automated malfunction procedures with automated trouble shooting. The cost of these few jobs in time, in data processing system memory, and in software programing was excessive. Hopefully, the data processing systems in the Space Station will handle the Appendix requirements cheaply and efficiently. It is recommended that the Space Station Program carefully control automation and gradually phase it into Space Station operations. Anything near total automation of the Appendix items will surely slip the IOC of the Space Station. This is because of the significant but now hidden automation burden of time, manpower, software, and dollars.

APPENDIX D - TRANSMITTAL LETTER OF NASA ADMINISTRATOR

Source: NASA Advanced Technogoly Advisory Committee (ATAC), Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, Progress Report 4, NASA TM 89811, May, 1987, pp. 48-50.

NASA

National Aeronautics and
Space Administration

Washington D C
20546

Office of the Administrator

DEC 10 1986

Honorable Edward P. Boland
Chairman
Subcommittee on HUD-
Independent Agencies
Committee on Appropriations
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As you know, the Congress directed, in Public Law 98-371, that NASA establish an Advanced Technology Advisory Committee (ATAC), in conjunction with the Space Station program, to identify specific Space Station systems which advance automation and robotics (A&R) technologies. The initial recommendations of the ATAC were transmitted to the Congress in March 1985. A further requirement of P.L. 98-371 is that the ATAC follow NASA's progress in automation and robotics for the Space Station, and report to Congress semiannually. Transmitted herewith is the third progress report of the ATAC.

This report acknowledges that "major progress has been made in the definition and preliminary design of applications and technologies for automation and robotics on the Space Station," and that "substantial progress has been made in the development of a U.S. telerobotic capability for the initial Space Station." However, at the same time, the report outlines a series of shortcomings in NASA's current efforts. I intend to have these matters addressed, and the Associate Administrator for Space Station, Mr. Andrew J. Stofan, has already undertaken significant steps toward this end. A synopsis of the current ATAC progress report is presented below, followed by descriptions of the corrective measures taken by the Space Station program.

- Major progress in definition and preliminary design of applications and technology for Space Station A&R is sufficient to merit extensive inclusion of A&R in the initial operating capability and growth Stations. NASA agrees that significant work has been accomplished, and intends to capitalize on it through Phase C/D and beyond. The potential enhancement resulting from the use of A&R has also been stated by the Critical Evaluation Task Force in its redefinition of the Program. No firm conclusions have been reached, however, on the appropriate level or timing of A&R capabilities.

- Planning for operations and system autonomy is not progressing quickly enough to influence design, and the benefit in life cycle costs offered by advanced automation is not being appreciated or balanced against initial cost. NASA acknowledges that, to date, the emphasis on an architectural approach to satisfy a diverse set of users has been far greater than on operations. However, program planning is now entering a phase in which the deficiencies cited by ATAC should be overcome.

  In mid September, the Operations Task Force (OTF) was organized and chartered to study Space Station operations and to provide timely recommendations for the Phase C/D RFP. We scheduled intensive briefings for the OTF on A&R applications and opportunities and expect them to formulate an operations concept that includes consideration of A&R and initial costs in evaluating design tradeoffs.

- A&R considerations must be given high priority in the Phase C/D procurement process. NASA fully concurs with this finding, and the Program is developing the Phase C/D RFP documents in a manner which explains the position which NASA wishes to take with regard to A&R (including design knowledge capture). A requirement is imposed that all RFPs contain equally explicit language on the value of A&R to the program and importance of the various benefits expected from A&R applications. We will also include in the evaluation criteria section of the RFP precise guidance regarding the importance of the quality and quantity of A&R applications.

- NASA is perceived as not committed to the inclusion of A&R recommendations in the Program. NASA believes that such a perception is a consequence of the predominant focus to date upon the Space Station architecture. However, a series of steps have been undertaken by the Program to correct this perception:

-- the appointment of a Division Director at Level A with direct responsibility for A&R, and a planned organizational element at Level A', reporting directly to the Program Director, responsible for A&R coordination across work packages and for program-wide tradeoffs;

-- enhanced programmatic capability in system analysis, engineering and integration through the establishment of the Level A' organization and pending selection of a strong supporting contractor; such a capability will enable performance of trade-offs and examination of options which will result in an optimal plan for A&R applications;

- -- appointment of an A&R advocate to the procurement working group supporting the coordination of the Phase C/D RFPs; and,

- -- the establishment of the Operations Task Force;

- o <u>Use of the Space Station Flight Telerobotic System (FTS) has not been planned</u>. As of the date of the printing of the ATAC progress report, only a preliminary plan for the FTS was in place. However, since receiving the responsibility for development of the FTS in May 1986, the Goddard Space Flight Center has been assembling a strong team and developing a detailed program plan. A preliminary set of requirements has been formulated, and final requirements, suitable for inclusion in an RFP, are expected in January 1987. The FTS RFP will be a separate procurement from the balance of Work Package 3, in an effort to incorporate the widest range of the most advanced technologies. Furthermore, recognizing the principal uses of the FTS, NASA has formulated two teams focusing upon assembly/maintenance and servicing, at the Johnson Space Center and Goddard Space Flight Center, respectively. These teams are examining the systems aspects of those functions, and formulating "architectures" for their performance using the capabilities available through both the FTS and extra-vehicular activity.

I believe the foregoing demonstrates that the Program is taking heed of the constructive advice offered by the ATAC, and is thereby increasing the Program strength in the important field of automation and robotics.

In closing, I would like to take this opportunity to note that with my recent appointment of Mr. Aaron Cohen as Director of the Johnson Space Center, the ATAC has lost a most effective Chairman and enthusiastic A&R advocate. I have appointed Mr. Robert A. Nunamaker, Director for Space at the Langley Research Center, and a charter member of the ATAC, to succeed Mr. Cohen as ATAC Chairman, to insure a continuity of outstanding leadership.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable S. William Green

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