NASA Contractor Report 3736

Space Applications of Automation, Robotics and Machine Intelligence Systems (ARAMIS) - Phase II

Volume 3: Executive Summary

D. L. Akin, M. L. Minsky, E. D. Thiel,
and C. R. Kurtzman

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3.1 INTRODUCTION

3.1.1 CONTRACTUAL BACKGROUND OF STUDY

On June 10, 1982, NASA Marshall Space Flight Center (MSFC) awarded a twelve month contract (NAS8-34381) to the Space Systems and the Artificial Intelligence Laboratories of the Massachusetts Institute of Technology, for a study entitled "Space Applications of Automation, Robotics, and Machine Intelligence Systems (ARAMIS), Phase II, Telepresence". This Phase II contract immediately followed the completion of the ARAMIS Phase I research (also contract NAS8-34381) which produced its own final report. The Space Systems Laboratory is part of the MIT Department of Aeronautics and Astronautics; the Artificial Intelligence Laboratory is one of MIT's interdepartmental laboratories. Work on the contract began on June 10, 1981, with a termination date for Phase II on June 9, 1983.

This document is the final report for Phase II of the ARAMIS study. The NASA MSFC Contracting Officer's Representative is Georg F. von Tiesenhausen (205-453-2789).

3.1.2 CONTRIBUTORS TO THIS STUDY

The members of the study team are listed in Table 3.1. Information necessary for this study was obtained from experts in government, industry, and academia, and from literature searches.

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Research Staff:
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Part-time Researcher: Antonio Marra, Jr.

TABLE 3.1: STUDY PARTICIPANTS

3.1.3 ORGANIZATION OF THE FINAL REPORT

Volume 1 of this report is the Telepresence Technology Base Development. This volume defines the field of telepresence, and provides overviews of those capabilities that are now available, and those that will be required to support a NASA telepresence effort. This includes investigation of NASA's plans and goals with regard to telepresence, extensive literature search for materials relating to relevant technologies, a description of these technologies and their state-of-the-art, and projections for advances in these technologies over the next decade. Also included is a listing of facilities that are doing research and development relating to telepresence. A technology development program leading to the deployment of an operational telepresence system by 1992 is presented. Volume 1 of this report is intended as a broad approach to telepresence technology and the general development of that technology.

Volume 2 of this report is the Telepresence Project Applications. This volume examines several space projects in detail to determine what capabilities are required of a telepresence system in order to accomplish various tasks, such as servicing and assembly. The key operational and technological areas are identified, conclusions and recommendations are made for further research, and an example developmental program is presented, leading to an operational telepresence servicer. Volume 2 is intended as an example of telepresence technology, and the associated issues, when telepresence is applied to several specific space missions.

Volume 3 is the Executive Summary of this contract report. It contains brief analyses supporting the major conclusions of this report (listed below).

- Telepresence is necessary and desirable.
- Telepresence is applicable both to general mission scenarios, and to specific spacecraft designs for servicing, structural assembly, and contingency operations.
- Telepresence should be able to match EVA in capability.
- Telepresence is feasible, both operationally and technologically.

- A working telepresence unit could be developed, built, and flown by 1990-1992.
- Advanced telepresence systems will be capable of very complex operations and high levels of autonomy.
- A research and development program should begin immediately.

A complete bibliography is included in both Volumes I and II.

3.1.4 TELEPRESENCE DESCRIPTION

For the reader not familiar with telepresence, this section is intended as a brief introduction to the concept of telepresence and some of the terminology used in this report. Figure 3.1 shows a telepresence spacecraft servicer concept developed by the MIT Space Systems Laboratory.

Roughly translated, the word "telepresence" means remote presence, just as "teleoperator" means remote operation. One way to think of telepresence is as a high fidelity teleoperator system. A teleoperator receives instructions from a human operator, and performs some action based on the instructions at a location remote from the human operator. It is similar to an industrial robot, except that a human is in control instead of a computer.

The distinction between telepresence and teleoperation is in the capabilities of the manipulators, and the quality and quantity of information available to the operator.

TELEPRESENCE DEFINITION

AT THE WORKSITE, THE MANIPULATORS HAVE THE DEXTERITY TO ALLOW THE OPERATOR TO PERFORM NORMAL HUMAN FUNCTIONS

AT THE CONTROL STATION, THE OPERATOR RECEIVES SUFFICIENT QUANTITY AND QUALITY OF SENSORY FEEDBACK TO PROVIDE A FEELING OF ACTUAL PRESENCE AT THE WORKSITE

The operator uses motions similar to those which he/she would use at the worksite to control manipulators capable of accomplishing operations. The

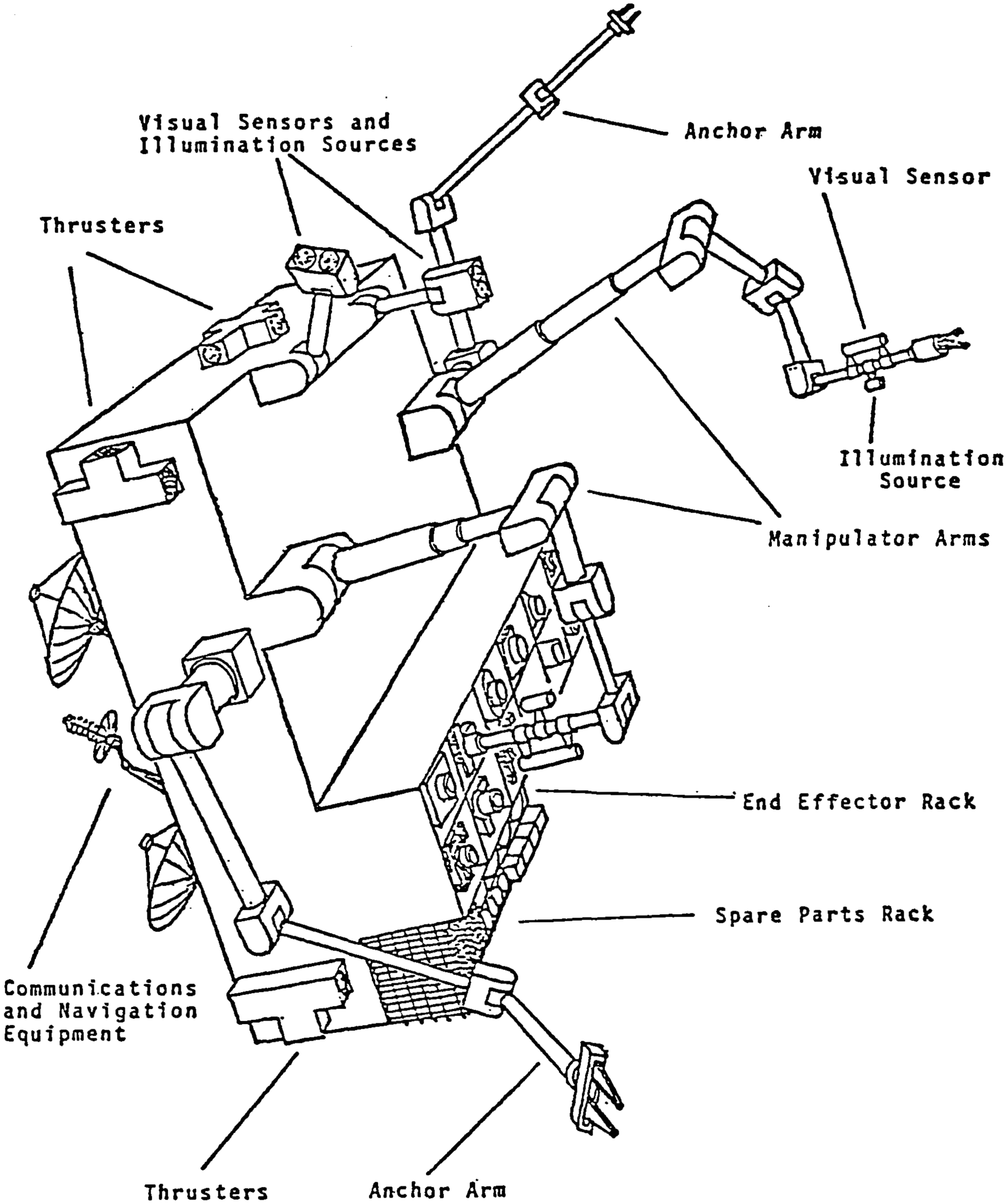


Figure 3.1: Conceptual Telepresence Servicer Unit

information available to the operator should maximize the feeling of being present at the worksite. This permits the operator to concentrate on the work using his/her natural abilities to perform the task, without being distracted by unnecessary differences between actually being present and using a remote system.

The purpose of a telepresence system is to perform space operations which require human intelligence, control, and dexterity when EVA is not possible, not desirable, or when EVA alone cannot accomplish the desired mission. A telepresence system should permit remote assembly and repair of spacecraft. Also, it will permit unanticipated problems to be solved. Skylab, Apollo 13, and the planned repair of the Solar Max spacecraft all demonstrate the importance of human capabilities for solving problems. Fortunately, humans were onboard both Apollo and Skylab to perform repairs, and Solar Max is within EVA range, but failures will occur on spacecraft which are out of EVA range or time limits. Telepresence is a necessary part of future space operations.

3.2 THE NEED FOR TELEPRESENCE

3.2.1 INTRODUCTION

To determine the technology required for telepresence, the general tasks of a telepresence system must first be understood. Volume I considers NASA goals and plans in a general sense, both near and far term. Telepresence is summarized as the ability to perform certain broadly defined functions. Volume II of this report considers the application of telepresence to specific spacecraft programs, and examines the details and operational considerations of telepresence operations. The telepresence technology base (described in sections 1.3 and 1.5) is based upon the need to perform the telepresence functions developed in this section.

NASA's plans can be divided into near term (through about 1995) and far term (post 1995). There is necessarily some overlap between these divisions because of planning and scheduling uncertainties, but there is a clear difference in the levels of planning detail for these periods. Near term plans and goals are detailed enough to permit reasonable assumptions about missions and procedures; these assumptions are sufficient to determine technology requirements. Far term plans are not specific enough to permit a determination of technology requirements beyond identifying general areas of research interest.

Any estimation of the proper technology to be used to solve a future problem will be heavily influenced by the available and currently projected technological capabilities in the problem area. Thus, the technology requirements in Volume I, section 1.3, consider applicable any technology which could be developed, space qualified, and integrated into a space telepresence system which has an initial operational capability of 1990 to 1992.

3.2.2 NEAR TERM GOALS AND PLANS

The near terms goals and plans can be divided into three areas; spacecraft servicing, structural assembly, and contingency events.

3.2.2.1 SPACECRAFT SERVICING

Servicing is the most important area for near term telepresence application. NASA is firmly committed to servicing such spacecraft as Space Telescope, the Advanced X-ray Astronomy Facility (AXAF), and the Long Duration Exposure Facility (LDEF). In addition, the success of the Solar Max Mission depends on an EVA repair scheduled for STS 13. Also, servicing is virtually mandatory for large scale space processing of materials, for space stations, and for space operations in general. Such large scale projects may not be fully developed by 1995, but the technology must be developed and in place prior to full scale operations to provide servicing as needed.

A key problem with servicing planning is the "inertia" in spacecraft design and future planning. This inertia is endemic in the aerospace industry, but is particularly noticeable in servicing plans.

Essentially, the problem is that almost any servicing function can be performed with low level or near present technology, if the spacecraft is specifically designed to accommodate servicing performed by that type of technology. The end result is that servicing planning is currently limited to either simplistic module exchange devices or EVA operations. More advanced approaches (telepresence) are not being planned for because the technology is not being developed, and the technology is not being developed because there are no planned uses for it. This statement does not hold true for long term plans because some of the missions, by definition, require dexterous operations beyond EVA altitude and time capabilities, but telepresence capabilities will be desirable prior to 2000.

Using more advanced technology, such as telepresence, has several advantages over low level technology such as non-dexterous module exchange devices. In general, the more advanced the servicer, the less impact servicing will have on the spacecraft design. Also, the advanced technology increases the reliability and versatility of the entire system. Consider the case of a jammed module or servicer arm. A module exchange mechanism could do little to solve the problem, and could conceivably be unable to detach itself from the crippled spacecraft, thus rendering both itself and the spacecraft useless. A more advanced teleoperator with two arms might be able to solve the problem; at the least it should be capable of freeing itself from the spacecraft. Such a system would also be capable of handling some contingency operations (see section 1.2.2.3).

3.2.2.2 STRUCTURAL ASSEMBLY

NASA's near term plans do not explicitly call for structural assembly, but operations of this kind will probably be used for space station and other pre-1995 missions. Also, a system capable of performing near term servicing tasks is probably capable of performing many structural assembly tasks.

Most of the tasks required for structural assembly are simple positioning and manipulation operations, which should require less dexterity than servicing tasks. Some other capabilities are required for some assembly scenarios, such as cutting and welding, and can be accomplished with various tools or end effectors.

The assembly of a structure requires the positioning and attachment of structural elements based on the assembly status of many other components in the structure. It is unlikely that a project of any size will exactly follow a preset construction plan; components will not always be exactly where they are expected nor behave in an expected manner. Also, the development of such an exact plan may be infeasible for many structures because ground simulations of space operations are not completely reliable. Thus, human control is necessary to provide the judgment and decision making capability required to cope with such a complex environment.

3.2.2.3 CONTINGENCY EVENTS

Discussion with NASA representatives indicates that the ability to handle contingency events is a priority capability. An examination of the Skylab or Apollo programs indicates that contingency operations have been of enormous benefit to the space program.

Less dramatic reasons exist for a contingency capability. On-orbit failures of spacecraft will become more common as the space program transitions to a space industry. Contingency repairs, such as the Solar Max repair, will be a necessary part of our space operations. Other, more complicated or dangerous tasks (replacing a failed battery or fuel tank, rescue operations, etc.), may exceed the EVA operations envelope and require a teleoperator mission. A spacecraft which has stopped communicating would require either EVA or a teleoperator of some type to approach it and make a diagnosis.

These contingency events may seem rather advanced for near term consideration, but they are possible events, which are, by definition, unplanned and unanticipated. Also, the repairs performed by a telepresence system would be determined by the details of the individual case and the technology available. An example of this is the Skylab program, in which the repair procedures developed were based on the capabilities and limitations of extra vehicular assembly.

3.2.2.4 NEAR TERM TASK SUMMARY

Table 3.2 is a listing of the basic tasks which the study group has developed. The tasks are meant to be representative of the activities which are necessary for NASA to accomplish its goals, particularly spacecraft servicing, but are not intended as an exhaustive list of possible telepresence capabilities. These tasks are used to develop the telepresence technology requirements presented in section 1.3. An advanced telepresence system would be capable of more intricate tasks than those listed in Table 3.2.

OPERATE MECHANICAL CONNECTION
OPERATE ELECTRICAL CONNECTION
OPERATE LATCHING DEVICE
GRASP OBJECT
POSITION OBJECT
OPERATE CUTTING DEVICE
OPERATE WELDING DEVICE
GRAPPLE DOCKING FIXTURE OR HANDHOLD
OBSERVE SPACECRAFT/COMPONENT

TABLE 3.2: TELEPRESENCE TASK SUMMARY

These tasks are general in nature, and each could be either very simple or very complex. They are intended as a listing of basic mechanical operations, which can be combined to perform near term spacecraft servicing, structural assembly, and contingency events.

A brief consideration of spacecraft design, and the necessary characteristics of any system capable of performing spacecraft servicing, indicates that remote manipulators similar to those used on the ground today could accomplish these tasks. They would be slower and exhibit more difficulty than would a human in a shirt sleeve environment, but they could perform the necessary operations. In summary, the near term requirements are fairly simple mechanical operations which are within the capabilities of present ground manipulators.

3.2.2.5 EVA EQUIVALENT CAPABILITY

A comparison of the tasks listed in Table 3.2 with past EVA operations and neutral buoyancy simulations for Space Telescope and other missions indicates that the tasks required for NASA's near term goals could all be accomplished by EVA. This is not surprising, since most servicing plans call for EVA to perform the servicing. However, a consideration of reasonable manipulator and servicer technologies also leads to combinations of simple mechanical operations, which are similar to EVA tasks.

In addition to the fact that near term telepresence tasks are similar to EVA capabilities, there are several other justifications for designing near term telepresence systems to match EVA capabilities. NASA has experience with EVA operations, and this experience will continue to grow as the STS program continues. Since the Gemini program, NASA and industry have been accumulating design experience for EVA hardware and procedures. This experience is growing rapidly through programs such as Space Telescope, and efforts are being made to standardize spacecraft fittings and connections to facilitate space operations. This experience has produced confidence that EVA is capable of performing useful and important tasks. A telepresence system with capabilities similar to EVA would be able to utilize this experience in design and operations. It would also only need to demonstrate its ability to perform EVA tasks in one or two comprehensive tests to be considered capable of a wide variety of space tasks. A system with radically different capabilities than EVA would require more time and testing before confidence in its abilities could be established. Also, EVA and telepresence systems with similar capabilities would be capable of mutual backup operations and simultaneous operations. This would be especially useful during initial testing, and during very difficult operations. Furthermore, a telepresence system with an EVA equivalent capability would provide for a smooth transistion from our present technology of all EVA to a more advanced man-machine mix. Spacecraft designed for EVA or telepresence servicing would be serviceable by both methods. Spacecraft designed for EVA servicing would be only slightly different from those designed for telepresence servicing, due mostly to size and reach differences. This is not as important for non-Low-Earth-Orbit (LEO) spacecraft because they are currently inaccessible to EVA, but near term servicing and assembly operations will be performed in LEO.

Finally, EVA equivalency does, by definition, include the ability to perform simple contingency operations.

It should be pointed out that the EVA equivalent capability does not mean that the telepresence system would perform the same tasks in the same manner as EVA. Telepresence might take longer, require more tools, and follow different procedures than EVA, but it would achieve the same results. Also, this EVA capability is based upon present suit technology. Future suit technology should significantly improve dexterity. Since both manipulator, end effector, and suit technologies are advancing, EVA and telepresence should continue to complement each other's operations through 2000.

3.2.3 LONG TERM PLANS AND GOALS

NASA's long term plans and goals are not specific or certain enough to permit definite conclusions other than general areas of interest. These areas of interest, or general goals, correspond closely with the potential future capabilities discussed in section 3.3.2 Advanced Technology. NASA will be able to utilize advanced technology, which is a natural product of present and near term research, to meet its long term goals. Unlike the technology necessary for near term telepresence, much of the advanced development will be performed by research in artificial intelligence and supervisory control which is not funded by NASA, although NASA support will be required to develop advanced AI technologies for space use.

The most important long term goals are increased system dexterity and the ability for contingency operations. As space operations become space industry, and the construction, modification, and repair of orbital systems becomes routine, onsite high dexterity manipulation will be mandatory. Equipment shipped from Earth will not be preassembled as it is today, but will arrive as spares and components for orbital construction and assembly. Some of the components will probably require high dexterity assembly. More importantly, the need to replace damaged and failed components, particularly in intricate mechanical devices or complex systems, will require dexterity simply to access the repair site. An example is the modification or repair of a wiring harness. Despite clever design and much effort, there will be places where wiring will need to be guided through a harness that is difficult to reach, and which requires hand dexterity to feed the wiring.

The potential size and scope of future space operations will prohibit the extreme caution and highly detailed planning that accompanies present space missions. Commercial space missions will be commonplace, and industrial accidents will occur. The failure of a large materials processing furnace or a high pressure fuel line implies the need for crew rescue and versatile repair tasks. Tasks of this nature necessitate the ability to deal with nonfunctional and severely damaged equipment in an environment which may be unsuitable for EVA. The probability of successful advanced contingency operations is improved greatly by the availability of high dexterity telepresence.

Driven partly by the scope of future operations and partly by the fact that transmission time delays may degrade dexterity, increased system autonomy is desirable. Many future tasks could be repetitive and boring; high level supervisory control for these tasks would relieve operator fatigue and improve reliability. In regions of obscured communications, an autonomous operation capability is necessary. Transmission time delays may make remote high dexterity control difficult or impossible, so some otherwise mundane tasks could require supervisory control or autonomy.

Due to the large costs of space vehicles, improvements to the telepresence system should be evolutionary, so that a new spacecraft is not required for each system upgrade. As spacecraft technology improves, the maneuvering system and telepresence unit may be replaced, but manipulator or computer system upgrades, for example, should not require replacing the entire spacecraft. The most radical advances in telepresence technology will occur in computer hardware and software, manipulators, and end effectors. Once a high dexterity manipulator is developed and installed, most system changes will be in software, which can be performed remotely from ground or space station control centers.

3.2.4 TELEPRESENCE PLANS AND GOALS CONCLUSIONS

For near term space operations, telepresence systems should be designed to be equivalent to EVA in capabilities. Telepresence may use different methods and may require more time to perform a given task than EVA, but telepresence should be able to achieve the same results. An EVA equivalent capability is desirable because it is more reliable than less capable options, such as the module exchange mechanism previously discussed, and is necessary for a minimum contingency operations capability. Also, an EVA equivalent telepresence system would have the option of using EVA as a backup and vice versa. Given the state of the technology presented in Volume I, section 1.3, and summarized in section 3.3.1, an EVA equivalent telepresence system is a reasonable and timely development.

Long term telepresence goals are increased dexterity and autonomy. A rapidly growing workload composed of increasingly complex tasks will require high dexterity manipulators and end effectors. The potential size and scope of future space operations and the desire for advanced contingency operations indicate that autonomy is an important goal.

3.3 TELEPRESENCE FEASIBILITY

This section summarizes the technology requirements and assessment, the facilities assessment, and the development program presented in Volume I, and the telepresence application to specific space missions presented in Volume II.

3.3.1 TELEPRESENCE TECHNOLOGY

The primary technology requirements for a near term (1990-1992) telepresence system are summarized in Table 3.3.

- STEREO-OPTIC VISION SYSTEM--PREFERABLY COLOR--CAPABILITY TO SLAVE TO OPERATOR'S HEAD POSITION
- HEAD-MOUNTED VISION DISPLAY SYSTEM
- TWO 7 DOF MANIPULATOR ARMS WITH FORCE CONTROL
- TWO GRAPPLE ARMS OR ONE DOCKING DEVICE
- INTERCHANGEABLE END-EFFECTORS
- OPERATOR USES FORCE-INDICATING HAND CONTROLLERS OR EXOSKELETAL ARMS FOR CONTROL

TABLE 3.3: TECHNOLOGY REQUIREMENTS SUMMARY

HUMAN FACTORS

A technology requirement that does not appear in Table 3.3 is the utilization of human factors knowledge. For a telepresence system this can be summarized as minimizing the operator's workload (as is done with aircraft cockpit design), and making the operation of the system as "natural" as possible. In this context "natural" means maximizing the use of the reflexes and manipulative skills the operator has learned throughout his/her lifetime.

For example, virtually all humans are experts at controlling their own vision by turning their head to look at a desired object or scene. Thus, monitoring the operator's head position to control the cameras on the telepresence servicer is superior to requiring the operator to use switches to control camera position. There are exceptions to this conclusion; controlling multiple camera views might be simpler with switches or with a voice command system.

VISION

The recommended vision system uses stereo-optic vision to provide depth perception and the sense of 3D imaging, as is provided by the human binocular vision system. To provide the capability to slave the cameras to the operator's head position the video displays should be helmet mounted. This allows the display screen to always be in view, regardless of the operator's head position. It also permits a separate image to be presented to each eye (necessary for true stereo vision) without requiring complex or expensive optics, which can restrict operator movement and cause discomfort. The use of color is desirable because it aids in scene recognition and understanding for both man and machine.

The technology for this kind of vision system is well advanced and a black and white stereo helmet mounted video system has been developed and tested by the Naval Ocean Systems Center (NOSC), in Hawaii. The addition of color should present little problem and space qualified video cameras have been in use since the 1960's.

MANIPULATOR ARM

Manipulator arms with 7 DOF are desirable from a human factors viewpoint because they are similar to human arms and are thus easily controlled by a master-slave control system. In addition, 7 DOF are needed to be able to reach around objects or into confined spaces. Two arms are required because some space operations will need two arms to be completed. Also, the human operator is more familiar with controlling two 7 DOF manipulators than with one 7 DOF arm and one arm with less than 7 DOF. NOSC Hawaii has built and tested a system with two master-slave manipulator arms, and Martin Marietta has built a 7 DOF manipulator arm for Marshall Space Flight Center than can easily be adapted for space use. MIT is building a manipulator system for neutral buoyancy simulation of space structural assembly and for testing telepresence control technology.

Force control of the manipulator arm is necessary due to the very high stress loads that can be accidently applied without some limit on manipulator force. This control can be both total force limits which the manipulator will not exceed, and the ability to apply a force specified by the operator. Force feedback (sending the force data to the control site and allowing the operator to sense the force and limit it) is probably the most desirable technique, but time delays in the communications system could prevent the operator from sensing excessive force in time to prevent damage. Experiments have been performed with force limited manipulators, but further research is necessary before this control technology becomes operational.

A telepresence system working on a satellite or a construction site must be able to apply forces and torques to nearby spacecraft and components. During these operations the servicer (telepresence system) must hold its position relative to the worksite or it will drift away and be unable to continue to apply force to the worksite. Holding position by rocket thrust is difficult, wastes fuel, and may be impossible because the engines may not generate enough thrust to overcome the force applied by the manipulator arms.

Spacecraft docking has been performed since the 1960's and is a viable option for telepresence, but the telepresence system may have difficulty reaching the necessary locations at a worksite if it is constrained to one contact point. A solution is to use a second set of manipulator arms to grapple hardpoints (structural members, booster casings, Extra-Vehicular Activity (EVA) handrails, Remote Manipulator System (RMS) fixtures, etc.). This second set of arms need not be as sophisticated as the main arms to permit the telepresence system to grapple the worksite at a variety of locations. Since manipulator arms are a prerequisite for a telepresence system, the development of the less advanced grapple arms should not present any problems.

END EFFECTORS

The grappling of various hardpoints, the manipulation of objects, and the ability to use tools, are requirements that a near term telepresence system must meet. A mechanical hand or hand analogue is an option which, in theory, could perform these tasks. However, such a device would require a significant development effort, and it is unclear that it would be easily controllable in an environment with a communications time delay. Interchangeable end effectors have been demonstrated in the laboratory and can accomplish all near term telepresence tasks. Since they are specialized, many of these end effectors could perform better than a mechanical hand. The mechanical hand offers the advantage of high versatility, but at present it is not necessary. More advanced telepresence systems (post 1995) will probably need some form of mechanical hand to perform the complex tasks which they could encounter.

CONTROL

The two most promising techniques for operator control of the manipulator arms are force indicating hand controllers or exoskeletal master arms. A force indicating hand controller is a multi-DOF "stick" which the operator grasps. As forces are applied to the stick the manipulator moves at a velocity proportional to the applied force. If the manipulator is in contact with a spacecraft or component, it applies the same (or proportional) force to the object it is in contact with. The operator applies forces to the hand controller to "fly" the end of the manipulator to the desired location.

The other attractive option is a master arm that monitors the position of the operator's arm and commands the telepresence manipulator to a similar position. Direct force control is more difficult with this system than with a hand controller because the master arm responds to an applied force by moving, thus the operator is not as aware of the forces being applied as with the rigid hand controller. These exoskeletal controllers may use preset force limits instead of continuous operator force commands.

The nuclear industry has used a third option which is essentially a hybrid of the previous control methods. The operator grasps a hand controller which commands the grippers or end effector of the arm. The hand controller is attached to the end of a master arm which move in response to forces applied to the hand controller by the operator. The actual manipulator arm follows the movement of the master arm. Both master arm approaches would benefit from force feedback, but the effects of communications time delays make this a questionable option.

All of these approaches are within present technological capabilities and are effective means of controlling a manipulator. The force indicating hand controller is probably the best choice for a near term telepresence system, but comparative experimental testing of these techniques is necessary before a final determination can be made.

SENSORS

Proximity and force sensors for manipulator arm control are necessary to provide information to the operator and control system. Proximity sensors are a well developed technology and are planned for use with the RMS. Force and torque sensors of various designs are available. Adapting them for space use should present no problems.

COMMUNICATIONS

Communications with the telepresence unit are required for its operation. This can be accomplished using the K band single access links provided by the TDRSS spacecraft. Unfortunately, the minimum communications time delay for Low Earth Orbit (LEO) is 0.5 seconds. The delay can increase to 2.0 seconds if the control station must communicate with TDRSS via the NASCOM system, as shown in Figures 3.2 and 3.3. Since time delays degrade performance, the study group recommends that every effort be made to minimize the communications time delay. This may require placing the telepresence control station at White Sands, New Mexico, where the TDRSS ground control center is located.

PREDICTIVE DISPLAYS

Since the time delay cannot be completely eliminated from the communications system, predictive display technology should be investigated.

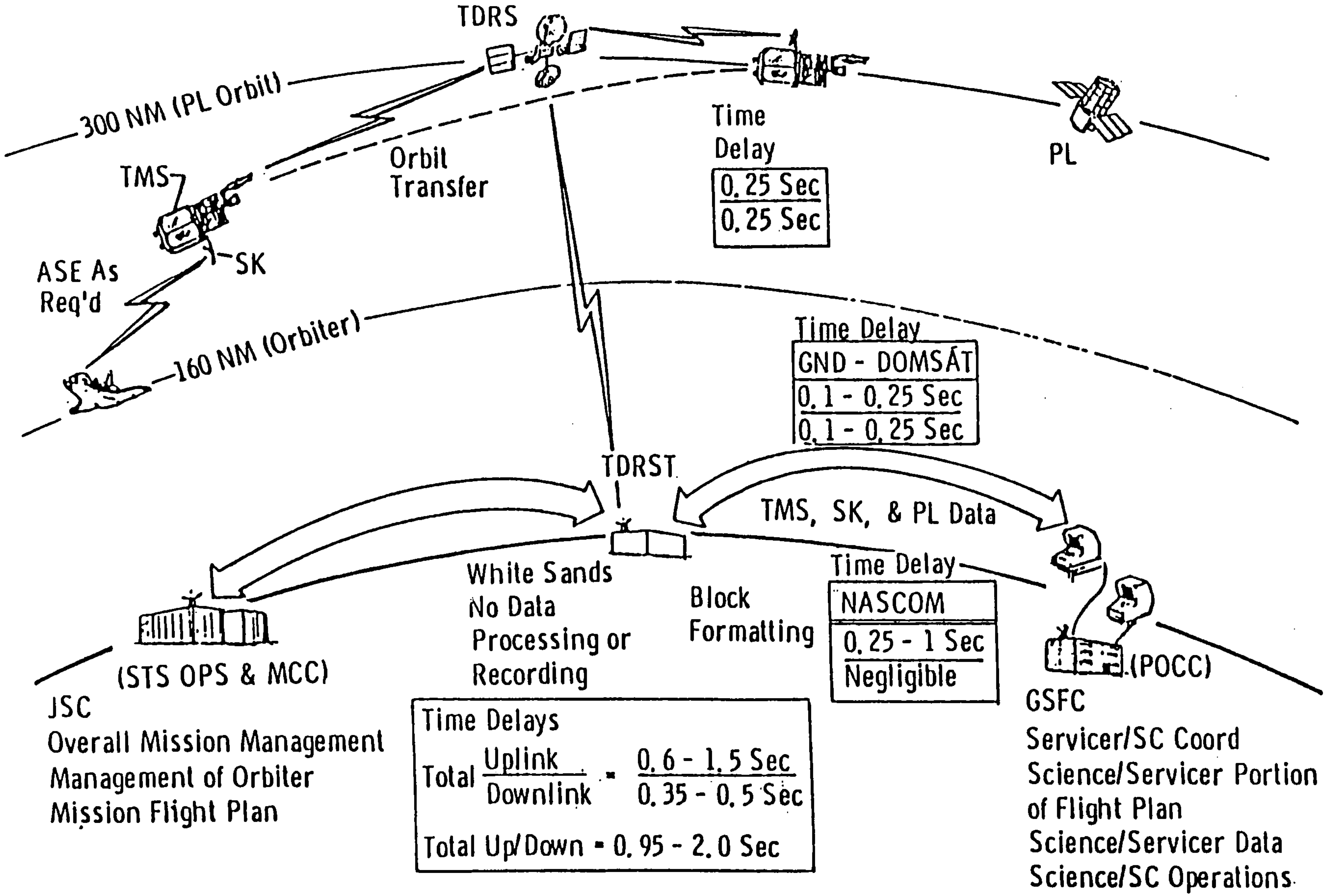
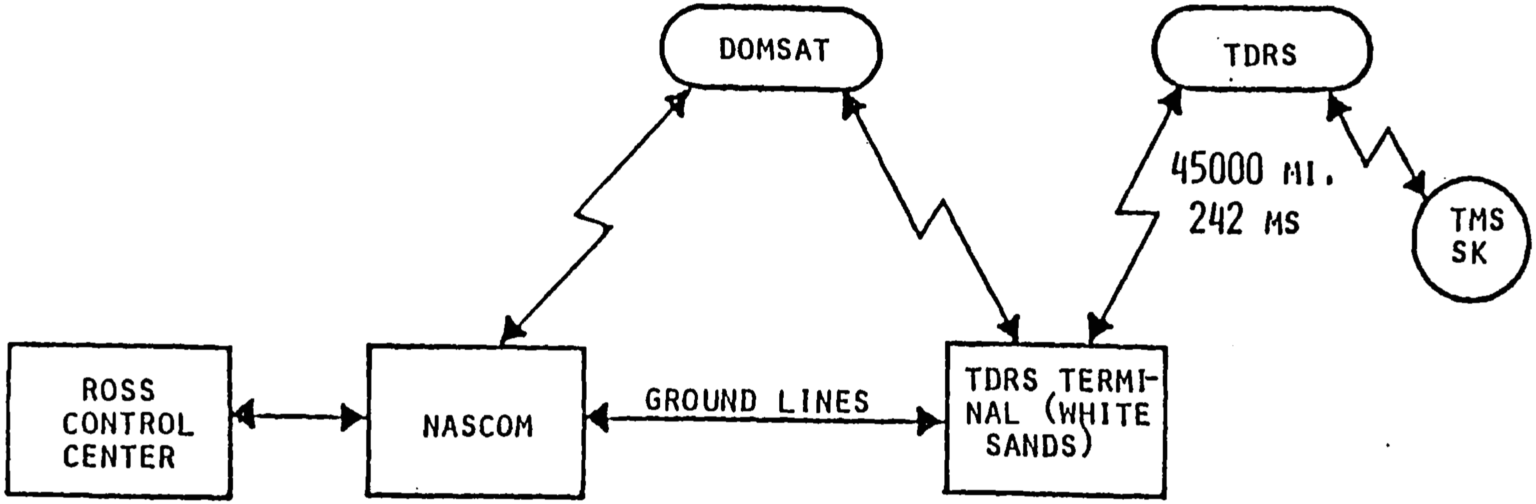


Figure 3.2: TDRSS Communication Links



DELAY	BLOCK FORMATTING	PROPAGATION	PROP	TOTAL DELAY
UPLINK (SEC)	0.25 - 1.0	0.1 (GND) - 0.25 (DOMSAT)	0.25	0.6 - 1.5
DOWNLINK (SEC)	NEGLIGIBLE	0.1 (GND) - 0.25 (DOMSAT)	0.25	0.35 - 0.5
			TWO-WAY DELAY =	0.95 - 2.0

Figure 3.3: TDRSS Time Delays

Recent advances in computer aided modeling (CAM) make predictive displays a potential method of eliminating many of the restrictions imposed by time delays. For example, a computer could store a model of a spacecraft, which would be updated and modified as the structure is altered by servicing. As the operator moves the manipulator, the computer would immediately show the operator where the manipulator links and end effector are positioned in relation to the spacecraft, even though the video response from the spacecraft had not yet been received. In this manner, many of the problems caused by the "move-and-wait" strategies usually employed in dealing with time delays are reduced. Predictive display technology has the potential to be very useful for telepresence systems, but several years of development work will be necessary prior to the production of a system suitable for operational use.

For a more complete presentation of telepresence technology see Volume I, sections 1.3 and 1.5, and Volume II, section 2.5.

3.3.2 ADVANCED TECHNOLOGY (LONG TERM TELEPRESENCE TECHNOLOGY)

The long term (post 1995) telepresence system will be able to take advantage of the advances in artificial intelligence. Advances in manipulator, sensor, and other technologies will have important effects, but the key to the system will be intelligent information processing and decision making.

Some of the technologies discussed in this section may be available prior to 1995, but many will require years of development, and may not be available until post 2000. The volatility and rapid expansion of computer and machine intelligence technology render forecasts in this area questionable.

The far term telepresence system will have two different modes of operation; full telepresence and advanced supervisory control.

3.3.2.1 FULL TELEPRESENCE

At this level, the operator actually feels as if he were at the worksite and performs naturally, taking advantage of experience, learned reactions, expertise, and human decision making abilites. This type of system should not require training beyond a simple introduction to the system, because it will operate in a manner similar to the human. The manipulator arms may not be anthropomorphic, but the system will accept and adapt anthropomorphic input. The system will have the capability to interact with the operator in natural language. An advanced "user friendly" telepresence system is not significantly more difficult to construct than one which is not user friendly. All of the developments necessary either make the system more effective (easy to use manipulators) or will be developed for other purposes, and could easily be incorporated into the system (natural language interfaces).

Some problems will still exist despite any advances. Time delays will always exist, as long as the worksite is a long distance from the control center. Predictive displays and possiblities such as predictive force feedback can reduce the effects of time delays, but not completely eliminate them.

3.3.2.2 SUPERVISORY CONTROL

The utilization of supervisory control technology does not have to wait until post 1995, but the more advanced forms discussed here will require advances in machine vision and artificial intelligence. Present supervisory control systems operate similarly to industrial robots. They cannot respond to changes in the environment, or to anomalous situations. More advanced supervisory systems will respond to higher level instructions, and will have the capability to perform complex tasks and make its own decisions. For example, it might understand and implement the instruction "replace amplifiers 6 and 7". It would look up the position of the parts, open the access panel, remove the module, replace the amplifiers, and return the module to its proper position. At this point the difference between autonomous operation and supervisory control becomes blurred. Thus, advanced supervisory control will be a natural step on the path to autonomous operations.

A telepresence system with advanced supervisory control has several desirable features. It is very useful for tasks which are severely impacted by the effects of transmission time delays. Such a system would rely on limited machine intelligence to deal with departures from nominal procedure. Since it would perform many tasks semi-autonomously, it would have reduced dependence on communications links and ground commands. Extra capabilities not found in human operators, such as infinte roll wrists, extreme patience, etc.) are easily incorporated in the system software. Tasks which are boring, fatiguing, repetitive, or otherwise distasteful to human operators can be performed by the supervisory control system.

All levels of supervisory control can be developed in parallel with the telepresence system. The supervisory system is implemented in software, and can be added to a telepresence unit with minimum impact on the hardware. Particularly advanced control modes may require upgrading of the onboard computers, but should not affect the rest of the system.

3.3.3 TELEPRESENCE PROJECT APPLICATION

In consultation with NASA MSFC, five space projects were selected for study:

- The Space Telescope (ST)
- The Advanced X-Ray Astrophysics Facility (AXAF)
- The Very Large Space Telescope (VLST)
- The Coherent Optical System of Modular Imaging Collectors (COSMIC)
- The 100-m Thinned Aperture Telescope (TAT)

These space projects were chosen to span the years 1985-2000, with ST representing a relatively near term potential telepresence application, AXAF being a mid-term application, and VLST, COSMIC, and TAT being far term applications with increased complexity and requiring technology well beyond the current state-of-the-art. Together the space projects cover a wide spectrum of tasks, such as spacecraft servicing, resupply, rendezvous and docking, and on-orbit assembly. The Space Telescope is the only space project which is certain to be implemented, although there is a high probability that AXAF will also receive a go-ahead. Even if none of the three far term space projects receive full funding and development, it is felt that the telepresence technologies and capabilities which they imply will be necessary in the late 1990's.

3.3.3.1 SPACE PROJECT TELEPRESENCE TASK ANALYSIS

Each of the five space projects has been analyzed to determine, to the extent that is currently possible, the nature of the activities which an on-orbit telepresence system should be able to accomplish. Documents supplied by NASA have been used as a basis for these evaluations. For the ST, the physical parameters of the structure are known in detail: this task therefore consisted of analyzing, at a nuts and bolts level, each of the tasks which will be necessary to perform ST servicing and maintenance. For AXAF, for which there are several tentative designs containing less detail than is available for the ST, this task consisted of evaluating anticipated telepresence requirements, and recommending modifications for the spacecraft to make it "telepresence friendly". Finally, for the advanced space telescope applications, telepresence requirements were evaluated at a very general level to determine appropriate areas for further research and development.

As an example, some of the analysis performed for ST is presented in the following section.

3.3.3.2 EXAMPLE TASK ANALYSIS -- ST SERVICING TASKS

Present plans call for the Space Telescope to be deployed and inserted directly into orbit by the Space Shuttle. Further, current plans are to have pressure suited astronauts (EVA) perform ST servicing. The ST has a design life of 10 years, but this could be significantly extended with on-orbit maintenance, ground maintenance, and ground refurbishment. The Space Telescope configuration has undergone extensive testing through the use of neutral buoyancy simulations, which have clearly delineated the steps necessary to maintain, refurbish, and perform selected planned and contingency operations in EVA. These simulations determined the type and location of crew aids which have been integrated into ST to facilitate EVA servicing of the spacecraft. The methodology developed, and the crew aids devised, are being used as starting points for future efforts in ensuring spacecraft serviceability.

Orbital maintenance is baselined for a total of 23 orbital replacement units (ORUs) aboard ST. These consist of:

- 5 Scientific Instruments (SIs)
- 3 Fine Guidance Sensors (FGSs)
- The Science Instrument Control and Data Handling Unit (SI C&DH)
- 3 Rate Sensor Units (RSUs)
- 3 Rate Gyro Electronics Units (RGEs)
- 3 Fine Guidance Electronics Units (FGEs)
- 5 Batteries

Further, on-orbit override of certain malfunctioning ST mechanisms (such as would be required by faulty Solar Array deployment) has been designed for on a contingency basis. A detailed analysis of each of these 23 tasks and the contingency operations in presented in Section 2.3.1. It is estimated that ST will require orbital maintenance anywhere from 2 1/2 to 5 years after initial deployment.

Ground maintenance is contemplated to replace hardware which cannot be replaced on-orbit, and to perform minor repairs (for example, the replacement of the Reaction Wheel Assemblies). This maintenance will be performed at

Kennedy Space Center to eliminate additional ST downtime for surface transportation.

After 10 years of orbital operation, it is estimated that ST will require major ground refurbishment. Major ST elements will be disassembled for extensive overhaul, including mirror recoating (if required). Scientific advancement and early ST science data may indicate a need for new scientific instruments, or the upgrading of those currently aboard ST. Orbital operational data will also be utilized to make hardware changes and improvements which will upgrade ST performance. While ground maintenance activities should be accomplished within 6 months, ground refurbishment would probably take a year or longer.

Telepresence is potentially capable of handling all orbital maintenance activities, as well as reboosting and orbital deployment from and retrieval to the Space Shuttle (with assistance from the Teleoperator Maneuvering System (TMS)). While EVA activities are currently planned for performing orbital maintenance functions, the implementation of telepresence could potentially reduce costs of maintenance operations, free the Shuttle and crew for other tasks, and offer other additional advantages. The cost reduction potential is due to spreading the non-recurring costs of a telepresence servicer over all the spacecraft it will service, rather than a single space project.

3.3.3.3 OPERATIONAL AND TECHNOLOGICAL ANALYSES

The operations and hardware analyses presented in section 2.3 of the report were used to determine the key operational (Table 3.4) and technological (Table 3.5) telepresence requirements. Each of these operational and technological telepresence requirements were discussed in detail in Volume 2 of this report to make specific recommendations as to their appropriate function, and necessary development, for a telepresence unit capable of servicing, or assembling the five spacecraft which were considered in this study.

RMS OPERATIONS
GRASPING
CONSUMABLE RESUPPLY
ASSEMBLY
ORBITAL TRANSFER
RENDEZVOUS
DOCKING
MIRROR CLEANING AND RECOATING
REMOTE OBSERVATION OF TELESCOPE SCIENCE DATA

TABLE 3.4: OPERATIONAL REQUIREMENTS

END EFFECTORS
SENSORS
VISION
CONTROL
HUMAN FACTORS
PREDICTIVE DISPLAYS
MANIPULATORS
STOWAGE RACKS

TABLE 3.5: TECHNOLOGICAL REQUIREMENTS

In addition to verifying the applicability of telepresence to various spacecraft missions, the telepresence applications analysis also produced important operational and technological results not identified by the technological analysis of Volume I. Two important examples are presented here.

Although it is feasible to place the telepresence servicer unit at the end of the RMS, the need for a TMS, or similar device, is critical. Without the TMS, the telepresence system is constrained to operate at shuttle altitudes, and probably similar mission time constraints. This would prevent the telepresence system from accomplishing many of the missions it is capable of performing, and remove many of its advantages over EVA. NASA should give the development of a TMS a very high priority.

From an operational point of view, the use of a space station as a base for a telepresence system is highly desirable. Any work done within range of the station communications systems could be performed without the undesirable communications time delays imposed by relay satellites. Since the telepresence system would always be in orbit, its availability would be much higher than a ground based system. Also, multiple sorties to a remote worksite become more feasible with a space based telepresence system. This increases the effective range of the system because the servicer does not have to carry all of the equipment necessary for a given mission. In addition, the servicer based at a space station would usually be available for work on or near the station. This could become critical during an emergency.

3.3.3.4 TELEPRESENCE APPLICATION SUMMARY

This analysis (presented in full in Volume II) showed that telepresence is capable of supporting the varied requirements of these spacecraft missions. In some cases, such as mirror cleaning and recoating, special auxiliary equipment may be necessary. The tasks required of telepresence by the spacecraft used in this analysis are representative of a wide variety of space operations, thus this analysis indicates that telepresence has the potential for widespread practical application.

3.3.4 FACILITIES

The facilities assessment performed in section 1.4 of Volume I indicates that expertise in the field of telepresence/teleoperation is divided between industry, academia, and government. The facilities for performing telepresence simulation and development exist, but they have suffered from a decline in funding during recent years. As a result, many of the research and development centers will need to update their equipment, particularly computers and control systems, in order to contribute to telepresence development.

3.3.5 DEVELOPMENT PROGRAM

In order to provide remote servicing operations during the early 1990's, a telepresence development program must be started immediately. Much of the necessary technology already exists, but a significant development effort will be required to integrate the technologies into an operational system, and space qualify the hardware.

Figure 3.4 presents the outline of a program which allows the evolutionary development of a space telepresence system. The first task, which should begin immediately, is the integration of the available technology into a ground demonstration system. This would allow the investigation of human factors and control system designs necessary for the development of an operational system.

In parallel with the ground systems integration, an experiment performed in the shuttle middeck would be used to verify the manipulator control system for actual zero-g operations. Ground tests can simulate much of the effects of the space environment, but manipulation of small masses cannot be accurately simulated on the ground. Their mass and inertia are dominated by the mass and inertia of a ground simulator and the contact dynamics are extremely difficult to model on a computer. An experiment in the orbiter middeck would allow low mass manipulation tests in zero-g, without requiring the construction of a vacuum rated system.

The results of the middeck experiment and the ground systems integration could be combined into a full scale demonstration and validation test on a pallet in the cargo bay. Other experiments onboard the orbiter could be performed as necessary along with continuing ground technology development.

All of these efforts lead to a 1990-1992 initial operational capability

EVOLUTION OF A SPACE TELEPRESENCE SYSTEM

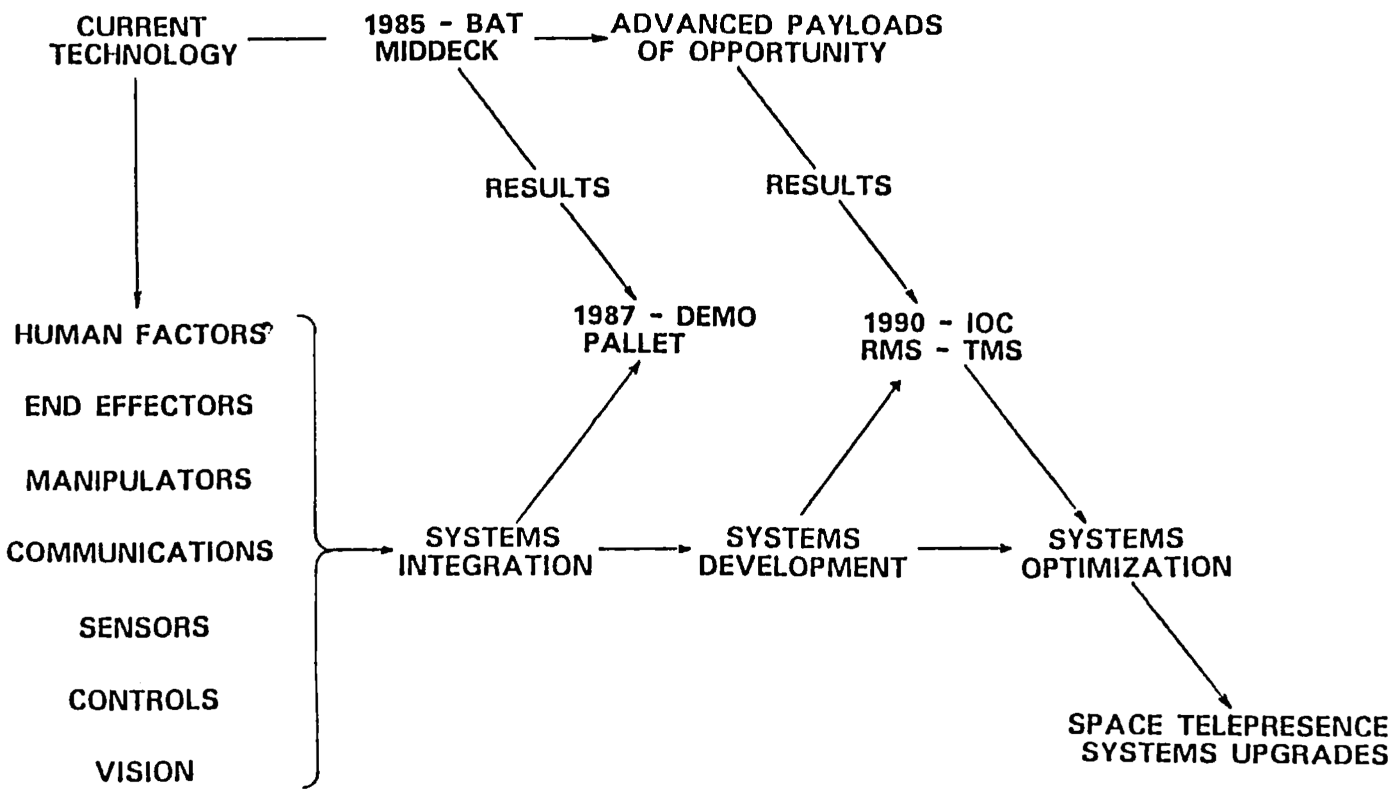


Figure 3.4: Development Program Outline

either for use on the TMS or as an attachment to the RMS for early operations. Continued systems development, most notably in software, and the addition of advanced technology when desirable, lead to a flexible and highly capable telepresence system.

Since the capabilities and expertise of NASA, industry, and academic institutions often overlap, and because each type of organization approaches the problem from a different perspective, each should participate in all phases of the development effort. The actual hardware necessary for a ground telepresence development system need not be very expensive, so NASA should encourage in-house, industrial, and academic ground development systems.

A ground development program, coupled with space experiments as necessary, will provide NASA with a highly capable and versatile teleoperation system able to meet both near and long term needs.

A more detailed technology development program is presented in section 1.5 of Volume I, and section 2.6 of Volume II.

3.4 CONCLUSIONS

3.4.1 TELEPRESENCE IS NEEDED

Future NASA plans, both short and long term, call for spacecraft servicing, structural assembly, and contingency operations. The success of large scale space operations, both for NASA and industry, will require the capability to perform versatile operations in space, similar to those associated with any large program on the ground.

Telepresence has the potential to be extremely useful in LEO, and, unless EVA becomes feasible at higher orbits, a necessary system for advanced space operations. The operational analysis of future space missions has found telepresence to be a desirable and feasible option for servicing, assembly, and contingency operations.

Telepresence is well suited to this demanding work environment because it provides both the ability to use human judgment and manipulative skill, and the ability to use autonomous technology (robotics) when it becomes available. Thus, telepresence has the advantages of both machine and human capabilities.

Due to the nature of near term spacecraft design, and the specifics of feasible near term technology (system deployment by 1992), the initial telepresence system should be designed to be capable of accomplishing the same tasks as an astronaut in a pressure suit (present EVA suit technology is discussed in section 1.2.2.5).

The lack of definite long term plans, and the rapid advance of electronics and control technology, make determination of specific long term telepresence objectives difficult. Since artificial intelligence and manipulator technology will continue to advance, as will the demands placed upon remote servicing systems, it is reasonable to conclude that long term telepresence systems will be capable of very complex mechanical tasks and high levels of autonomy.

3.4.2 TELEPRESENCE IS FEASIBLE

Most of the necessary technology for an EVA equivalent telepresence system has already been developed. Certain areas, such as vision systems, need development of specific components, such as small, lightweight color displays, but these areas are often being developed independent of NASA. Space adaptation and qualification of these technologies is also necessary, but the most important task is system integration. During this process, human operator interactions with the hardware and the control system must be analyzed to permit design of the actual flight system.

Telepresence technology, and the research centers involved with it, have been adversely affected by a lack of funding during the past few years, but the technology, facilities, and personnel necessary for the development of a telepresence system are available.

Research has now progressed to the point where experimental verification, and determination of the man/machine interactions of a telepresence system is a necessary next step. The study group strongly recommends that NASA begin a significant development effort immediately. If development of the necessary hardware and software commences immediately, a telepresence system could be assembled and flown by 1992. This date coincides with potential initial need for servicing operations and the possible assembly of a space station. The successful perfomance of one contingency operation during the deployment and assembly of the station could more than justify the cost of the entire telepresence development program.

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16. ABSTRACT

This report defines the field of telepresence, and provides overviews of those capabilities that are now available, and those that will be required to support a NASA telepresence effort. This includes investigation of NASA's plans and goals with regard to telepresence, extensive literature search for materials relating to relevant technologies, a description of these technologies and their state-of-the-art, and projections for advances in these technologies over the next decade.

Several space projects are examined in detail to determine what capabilities are required of a telepresence system in order to accomplish various tasks, such as servicing and assembly. The key operational and technological areas are identified, conclusions and recommendations are made for further research, and an example developmental program is presented, leading to an operational telepresence servicer.

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