HQ GRANT
IN-29-CR
51137
P-22

Final Report on the

NASA Headquarters Grant on Space Engineering

NAGW-21

November 1, 1979—March 31, 1991

Harold L. Alexander
Principal Investigator
Bradley Career Development Professor of
Aeronautics and Astronautics

Massachusetts Institute of Technology

October 29, 1991

(NASA-CR-187820) SPACE ENGINEERING Final Report, 1 Nov. 1979 - 31 Mar. 1991 (MIT) 22 p CSCL 22A

N92-11215

Unclas

G3/29 0051137

Section 1

Introduction

NASA Grant #NAGW-21 was awarded to the MIT Space Systems Laboratory (SSL) beginning in November 1979 to support research in human productivity in space, as well as in space telerobotics and automation. The grant also supported research in the control of large flexible space structures, but this segment of the effort was since transferred to Grant #NAGW-2014. This final report is intended to review the research conducted in productivity and robotics, and to provide a guide to the literature resulting from this research.

The SSL first set out to study human productivity for extravehicular tasks performed in microgravity, particularly including in-space assembly of truss structures and other large objects. This research peaked with the 1985 EASE-ACCESS flight of the Space shuttle, which saw the repeated assembly and disassembly in the Shuttle cargo bay of the MIT EASE structure, a tetrahedral assembly of truss beams connected to structural nodes with quick-connect joints. This flight experiment demonstrated the feasibility of human assembly of truss structures, and successfully tested several arrangements for astronaut support during Extra Vehicular Activity (EVA) including mobile astronaut foot restraints using the Remote Manipulator System (RMS) and free-moving, unsupported assembly.

During the same period, the SSL's human-factors research probed the anthropometric constraints imposed on microgravity task performance and the associated workstation design requirements. Anthropometric experiments included reach-envelope tests conducted using the Three-Dimensional Acoustic Positioning System (3DAPS), which permitted measuring the range of reach possible for persons using foot restraints in neutral buoyancy, both with and without space suits. These experiments revealed the very wide range of body motion that is possible in microgravity. In addition, a one-degree-of-freedom force-sensing hand-controller system and a multi-degree-of-freedom force-sensing system (FAFNIR), both designed for neutral-buoyancy research, permitted study of subjects' ability to apply and control forces exerted in neutral buoyancy with a variety of bodyconstraint arrangements.

Many of the SSL's early human-productivity research was conducted in neutral buoyancy, using the support of water to simulate the weightless environment of space. The SSL developed many systems and techniques for neutral-buoyancy testing, regularly testing at both the MIT Alumni Pool (the campus swimming pool) and the NASA Neutral Buoyancy Simulator at the Marshall Space Flight Center.

It became clear over time that the anticipated EVA requirement associated with the Space Station and with in-space construction of interplanetary probes would heavily burden astronauts, and remotely-operated robots (teleoperators) were increasingly considered to absorb the workload. The SSL's experience in human EVA productivity led naturally to teleoperation research into the remote performance of tasks through human-controlled robots. This was an excellent target for neutral-buoyancy research, which permits full three-dimensional vehicle mobility along with an excellent realization of the interaction forces between telerobots and their environment. Three such robots were built for this purpose, each one having a different purpose and design. These telerobots demonstrated a variety of teleoperation capabilities, including the possibility of performing complex construction tasks through remote presence without the immediate participation of human EVA crewmembers.

In the remainder of this report, each of these themes appears in detail, with reference to the associated research theses and other literature generated by the SSL. In addition, the continuing research activities of the Laboratory, that exceed the period of the subject grant, are presented and discussed for the reader's reference.

Section 2

SSL Research in Human EVA and Anthropometrics

The extravehicular, microgravity environment is a challenging place for humans to work. In the late 1970's, the advent of plans for the Space Station convinced members of the Space Systems Laboratory that improved understanding of microgravity task performance, under the conditions likely to prevail during Space Station construction, was necessary.

This conviction led, in the late 1970's and early 1980's, to a program of research at the MIT SSL to study human body dynamics during a variety of microgravity tasks, most particularly the assembly of large truss members into extended structures. Much of this work was aimed at determining the validity of neutral-buoyancy simulation as a technique for simulating microgravity, by conducting experimental assembly tasks in neutral buoyancy and by reproducing in neutral buoyancy certain tasks that had been performed and filmed in orbit. The following SSL reports relate to experimental activities in human on-orbit performance in neutral buoyancy and in orbit. [1,2,13,14,15,16,17,18,19,20,21,23,28,30,31,32,38,43,51,52,55,58,74,75,85,95]

This research strongly supported the effectiveness of neutral buoyancy for testing and practicing extravehicular microgravity assembly procedures. The research was then continued using neutral buoyancy simulation as a tool to examine the productivity of astronauts in realistic simulations of anticipated microgravity assembly tasks. This period of research was accompanied by the development by the Laboratory of truss assembly connectors and other devices to aid human-factors research and to suggest designs for use in orbit. [3,4,5,6,7,8,9,10,11,12,22,24,25,26,27,29,39,40,41,44,64,67,76,77,79,94] In addition to a prototype truss connector, the neutral-buoyancy Personal Underwater Mobility Apparatus (PUMA) was built to simulate the Manned Maneuvering Unit used in space, again to reproduce the conditions of in-space task performance. A new space suit glove developed by the Laboratory was intended to give astronauts improved dexterity in space. [33,34,59] And a series of space operations studies investigated microgravity task planning and analysis. [61,63,72]

This array of neutral-buoyancy research, and observation of actual microgravity performance by Space Shuttle astronauts, indicated that astronauts could indeed function in space at a high level of productivity. In order to fully establish this result, and to obtain an even more rigorous confirmation of the neutral-buoyancy results, the EASE experiment was proposed and carried out in 1985 to directly test and compare neutral-buoyancy and microgravity performance of a truss assembly. [45,48,53,54]

The EASE structure was composed of six cylindrical truss elements to be connected to one another by four apical elements into a tetrahedral shape suggesting the methane molecule. One apex was anchored in the Space Shuttle cargo bay, permitting the structure to be secured and repositioned during assembly. The structure combined various characteristics of a microgravity truss including a fully kinetically determinate "closed-box" construction. The apex connectors were of a design permitting straightforward operation by an astronaut wearing a space suit glove.

The results of the EASE experiment confirmed the optimistic predictions for EVA productivity, as the structure was assembled and disassembled several times on orbit in the allotted EVA time. The experiment included testing a variety of working arrangements for the astronauts, including the use of foot restraints at the tip of the Space Shuttle remote manipulator arm and free-floating assembly. The EASE experiment also permitted direct comparison of neutral-buoyancy and microgravity task performance, as the same task was performed and recorded repeatedly in both environments.

More recent astronaut EVA research has focused on other aspects influencing astronaut microgravity capabilities and workstation design, with particular application to on-orbit repair and servicing of satellites. Microgravity both helps and hinders in the performance of tasks on orbit. Not needing to support his/her body against gravity, an astronaut in foot restraints may assume a variety of body configurations that considerably extend his/her reach envelope relative to the foot restraints. On the other hand, use of foot restraints restricts astronaut mobility and when operating without foot restraints it may be very difficult for an astronaut to exert substantial forces and torques on objects within reach. Handholds certainly help, but bracing points for feet are required for exerting large forces or moments.

The SSL's anthropometrics research has therefore concentrated on finding the astronaut reach envelope both with and without the space suit (which substantially restricts motion) and on measuring applied-force capabilities within the workspace. The purpose of this work was to contribute to task design for astronauts in microgravity, and to establish limits on what can reasonably be expected of astronauts within a particular worksite configuration. The SSL's teleoperation research led to some of the earliest available results on astronaut EVA task performance. It also provided the SSL with the understanding and experience that was needed to launch neutral-buoyancy study of teleoperators and teleoperator performance of the same kinds of tasks that had been studied for human EVA. This research is the subject of the next section of this report.

Section 3

SSL Teleoperation Research

While the SSL's experiences with astronaut on-orbit task performance were generally encouraging, it became increasingly clear to NASA and to members of the Laboratory during the 1980's that very heavy demands would be placed on human EVA by Space Station activities. It therefore became important to understand how astronauts' efforts could be augmented through robotics and automation and by remotely-controlled robotic task performance.

The field of telerobotics concerns itself with robots, or mechanical manipulating and maneuvering devices, that are remotely controlled in "real time" by human beings. This means that a human operator directly controls the robots' maneuvering and manipulation devices to perform the necessary task, generally viewing the remote worksite through a visual interface system. The remote robot therefore takes on the hostile or inaccessible environment where the task must be performed, while the human operator provides the intellectual, sensory, and control functions from a safe control site. In the case of space EVA teleoperation, the worksite is rendered both uncomfortable and unsafe by the space suit, collision hazards, and microgravity, and by the lengthy procedures attending each EVA exit and return.

Because of its considerable study and experimentation with human performance of orbital EVA tasks, and its experience with the practicalities of neutral-buoyancy simulation, the Space Systems Laboratory was well situated to take on the study of microgravity teleoperation. [56,62,71,73,79,81,82,84,86,89] Neutral-buoyancy simulation of space telerobots uses underwater vehicles ballasted and trimmed to be neutrally buoyant in both depth and orientation, moving freely in the three-dimensional aquatic environment just as the space telerobot moves freely in space.

The first operational teleoperator vehicle in the Laboratory was MPOD, the Multimode Proximity Operations Device. [93] MPOD's primary function was to study docking maneuvers that permit one vehicle to be maneuvered and attached to another. This important function severely tests the ability to control the maneuvered vehicle, particularly during impact as the docking fixtures (male and female) of the two vehicles contact one another. MPOD is equipped with a forward-pointing docking fixture projecting approximately 1/2 meter in front of the vehicle that mates with a fixed docking target simulating the second vehicle.

Prior to the MPOD research, vehicle docking had generally been considered only where a human operator is present on the docking vehicle to directly observe and control the maneuver. It was therefore important to determine the relative efficacy of teleoperated docking, where the operator's view would be not direct but via a television camera mounted on the vehicle (or nearby) and providing the operator with a remote sense of vision. In order to permit comparison of "direct" control and teleoperation, MPOD was designed to be operated in a variety of direct-control and teleoperation modes–hence the "multimode" character of the vehicle. First, of course, MPOD was designed to be remotely operated from an above-water control station that included a video monitor projecting the view from a forward-pointing vehicle-mounted camera. Second, the vehicle-centered view could be replaced with a "third-person" camera viewing both vehicle and docking target, to simulate vehicle docking with this alternative visual feedback. Third, an underwater control station permitted controlling the vehicle using a direct, third-person view. Fourth, MPOD's body itself was built to accommodate a SCUBA diver to perform "direct" vehicle control using underwater controls, with either a direct view through the transparent front window of the vehicle or using an underwater television monitor to present the same views as the above-water control station. The importance of kinesthetic and vestibular motion cues (direct motion sensing) and of view angles could therefore be directly determined by comparing experiments with precisely controlled operator-vehicle relationships.

A variety of camera and control-station arrangements permitted further variation of the operator-vehicle relationship. A fixed-location, underwater control station permitted vehicle docking experiments using a direct, exterior view of the vehicle, while a fixed, remote camera permitted a parallel experiment to be conducted using the above-water control station.

MPOD's capabilities for vehicle-maneuvering experiments were impressive, but the vehicle was limited to tasks requiring no remote manipulation or assembly. The Beam Assembly Teleoperator (BAT) was built in order to directly compare teleoperator and human capabilities in tasks requiring transport and assembly of structural elements into truss structures, with application to the construction of large space structures such as the Space Station. [35,36,37,42,46,47,50,57,60,65,70,97] The purpose was to continue the Laboratory's research in on-orbit assembly, moving into teleoperator performance of the same tasks that had previously been studied with human astronauts directly performing these tasks.

BAT incorporated a variety of design advantages over MPOD. First, of course, the robot was provided with a variety of manipulators and claws that permitted carrying and connecting truss elements. A five-degree-of-freedom primary manipulator, controlled from a kinematically identical master arm mounted on the vehicle control station, performed the dextrous manipulation necessary to position and connect truss elements. Since each truss-element connection requires two items to be connected, a second arm was necessary: this was realized with a fixed claw that could grip a truss beam or node to fix the vehicle in place. A third, one-degree-of-freedom beam-carrier manipulator served for transporting and roughly positioning truss beams. In the "streamlined" orientation, the beam carrier arm holds the beam parallel to the vehicle's primary direction of travel, interfering as little as possible with BAT's motion. In order to position the beam for assembly, the beam-carrier is pneumatically actuated to swing the beam into position at the front of the vehicle adjacent to the claw and the dextrous manipulator.

BAT also incorporated greater capabilities for remote vision than did MPOD. Rather than using a single, fixed camera, BAT's stereoscopic camera pair can be panned and tilted to track the operator's head motion at the control station. The vision system thus permits the operator to "look around" in the vehicle environment through a helmet-mounted display and to enjoy a very striking sense of visual depth. This strongly enhances the operator's ability to perceive objects and targets in the remote environment, and to perceive and track BAT's motion there. BAT's second, fixed camera pair was normally used for navigation, where a strong sense of the vehicle's orientation and motion was important.

BAT has been used to reproduce many of the tasks that have been performed by human astronauts, including assembling a tetrahedral structure resembling the EASE structure, and a space station truss structure, in 1987. It has since been used to attempt a greater variety of servicing tasks in neutral buoyancy, particularly including the exchange of batteries for the Hubble space telescope.

Both BAT and MPOD are rather large vehicles, heavy and difficult to service and deploy conveniently. In an attempt to simplify vehicle operations and to achieve greater vehicle maneuverability, and to update the overall vehicle design, the ASTRO vehicle (Apparatus for Space TeleRobotic Operations) was developed. [91,92] Using a more compact design and updated electronic systems, ASTRO was intended to become a modular vehicle permitting incorporation of a variety of manipulator systems with a compact, serviceable maneuvering system. ASTRO has indeed proven itself as a serviceable motion bed, with potential usefulness as a "sheepdog" vehicle permitting remote observation of tasks involving other vehicles and astronauts.

Recent research using these vehicles has concentrated on achieving closed-loop control of their position and orientation based on a variety of sensors, in order to augment the operator's control as well as to improve simulation of microgravity vehicle dynamics. [68,69,70,78,80,87,88,90,92,96] In addition to pendular gages for sensing the local vertical, and angular rate sensors for sensing the vehicles' rotation, the 3DAPS (3-Dimensional Attitude and Position Sensing) system has been used with MPOD to estimate and control the vehicle's position and orientation in the water. 3DAPS is a hydroacoustic system based on measuring the transmission delay for sound pulses travelling from a set of "thumpers" to as set of vehicle-mounted thumpers. Unfortunately the noise and error properties of the 3DAPS system as well as its infrequent position updates have made such control very difficult. Substantial benefit has accrued, however, from the use of rate gyroscopes for vehicle rotation stabilization, and such methods hold promise for vehicle stabilization.

In addition, the 3DAPS system has been used to provide the controlling operator with visual cues, displayed on the remote-vision monitor, to represent MPOD's position and orientation relative to the docking target. [89] This information was intended to reinforce the direct visual cues to be had by looking directly at the remote image itself. While the problems with the 3DAPS system that are mentioned above prevented substantive results from being draw from the effort, it resulted in observations that have led to further research in augmented vision systems.

Section 4

Other SSL Research Efforts

In addition to the human-performance and teleoperation research above, the Laboratory has performed research under the subject Grant into novel alternative vehicle designs as well virtual-environment simulation of remote-vehicle control.

Perhaps the Laboratory's most unusual vehicle is a pneumatically-actuated walking robot intended to move along a truss beam in a "claw-over-claw" fashion. The simplicity of the walking motion permits a preprogrammed gait whereby each arm of the vehicle alternately swings up from the supporting bar, slides linearly to the front of the vehicle while the opposite claw slides to the rear, and then re-grasps the bar.

The Laboratory also developed a virtual-environment vehicle simulator simulating a remote vehicle maneuvering relative to a spinning spacecraft in low Earth orbit (including a rough depiction of Earth itself). The simulation was able to be observed and controlled from the same control station normally used to control MPOD itself.

As significant as the vehicles themselves, perhaps, has been the development of their associated control station. RECS, the Reconfigurable Electronic Control Station, is used with MPOD to provide the large monitor and control-input devices that constitute the human interface to the vehicle. In addition, it provides a number of monitors and keyboards for communicating with the computers involved in the vehicle's control. ICS, the Integrated Control Station, includes the helmet-mounted display and head-orientation tracking system that make up a part of the BAT visual interface system. The teleoperator master arm mounted on ICS also provides the important teleoperator link to the dextrous arm attached to that telerobot.

While it never became fully operational, the SSL teleoperation-simulation motion bed (the SIM room) represented an alternative to both neutral-buoyancy and virtual-environment simulation for teleoperation research. The five-degree-of-freedom motion platform was intended to be fitted with video cameras in order to simulate a maneuvering remote vehicle. The sixth, vertical degree of vehicle freedom was intended to be simulated by raising and lowering the space shuttle model relative to which the simulated vehicle was maneuvered. A high level of visual realism and a faithful reproduction of microgravity vehicle dynamics could be obtained by controlling the camera motion platform to respond to operator control inputs as would a simulated telerobot.

Drive-system design problems prevented the simulator room's ever becoming operational, but it has been modified and updated since the termination of the subject Grant to support development of machine vision systems for automatic sensing and control of remote-vehicle motion. This and other continuing research efforts are discussed in the following section.

Section 5

Future Directions: The Laboratory for Space Teleoperation and Robotics

Although NASA support for the Space Systems Laboratory has ended for now with the subject Grant, the lab is continuing its research in space teleoperation and robotics as the newly-named Laboratory for Space Teleoperation and Robotics (LSTAR). The following information about this new Laboratory's research is provided for readers interested in continuing research at MIT in space teleoperation systems.

The goal of this new Laboratory is to apply advanced systems design and systematic, effective human-factors research in order to develop and study advanced human-machine interface systems for teleoperation. Despite its name, the Laboratory is targeting the common elements of teleoperator systems to be applied in the land, sea, and air environments as well as in space. The Laboratory will concentrate on those aspects of teleoperator systems that strongly affect the success of teleoperation, most particularly the sensory and control interface that link the human operator with the remote robot. In addition, the Laboratory is working on autonomous robotic control to aid human telerobot operators. The current main thrusts of the Laboratory in this direction are focused on a new, advanced, neutrally-buoyant telerobotic vehicle called STARFISH, and on a virtual-environment system intended to test a broad variety of human-machine interface systems.

LSTAR's virtual-environment system is based on an IRIS 4D/20 Personal Graphics System that is shared by researchers in the Man-Vehicle Laboratory at MIT who are studying flight-plan information presentation in the cockpit. For LSTAR's purposes, a IBM-PC compatible computer connected to the IRIS converts operator control inputs into digital form and transmits them over a serial communications link. The IRIS processor calculates the responses of a simulated remote vehicle to the operator's inputs, and generates operator-feedback images based on this simulated vehicle's motion and on a graphical model of the vehicle's visual environment. These images may be presented either on a large-screen television monitor, on a stereoscopic helmet-mounted display worn by the operator.

This virtual-environment system permits testing a wide variety of operator-vehicle interface systems, simply and economically. Vehicle dynamics, camera pointing control (for simulated pan-and-tilt cameras), the visual environment, and control-device assignments are all under direct,convenient software control. The ease of controlling the experimental conditions, and the predictability of the virtual environment, make human-subject testing much more easy and effective then in neutral buoyancy, where vehicle dynamics are relatively hard to control, and where the vicissitudes of controlling physical remote vehicles may mask the relatively subtle effects being sought.

The point of this research is to lend to the remote-vehicle operator, as nearly as possible, the same easy and effective perception in the remote environments as if he/she were truly there. This is a challenging task, but it is crucially important in order to obtain acceptance of remote vehicles in highly safety-conscious environments such as the Space Station. An astronaut fitted with a Manned Maneuvering Unit (MMU) can very easily perceive and control his/her motion relative to the Station, and so avoid any hazardous loss of control. A primary difference between that astronaut, and an operator controlling a remote robot from within the safety of the Station, is that the remote-vehicle operator suffers from more restricted visual perception. If the remote-vision interface may be improved to approximate direct perception—and if the operator's control may be augmented with automatic systems—sufficient vehicle safety may be obtained to gain acceptance of remote-vehicle Space Station operations. If any perception of danger persists, however, conservatism and the general bias toward manned space operations will prevent acceptance of free-flying telerobots for EVA operations.

LSTAR's neutral-buoyancy program is aimed at developing the automatic-control and control-augmentation systems to help telerobot operators at their tasks. Point-to-point navigation, worksite stationkeeping, docking, and object positioning and grasping are all tasks that can be automatically programmed and controlled with modern sensing and control technology, and the Laboratory is determined to achieve the potential of these technologies. Such systems need to be tested and demonstrated in a laboratory environment, not in simulation, and they require modern technology and innovative design. STARFISH, LSTAR's laboratory telerobot, is designed to have the electrical power, the computational resources, the sensing and maneuvering capabilities to automate a wide variety of tasks including automatic position and attitude sensing and control, and a range of vehicle control augmentation modes.

The SSL's previous attempts at automatic vehicle control have been limited primarily by inadequate sensing. LSTAR's approach therefore began with identifying a position and attitude sensing system that would provide high resolution, frequent updates, and reliability. It was also important to find a sensing mode that was applicable to space, in order to obtain research results and control techniques that arguably could be transferred to that environment. Acoustic methods obviously are inapplicable in the vacuum of space while vision-based techniques, based on the currently advancing technology and increasing image processing power, hold great promise. The Laboratory is therefore developing passive-vision sensing systems that will be used in the coming year to obtain real-time motion control of the vehicle, for use in both stationkeeping control (to support telemanipulation using a vehicle-mounted manipulator arm currently being designed) and automatic point-to-point maneuvering.

STARFISH is also expressly designed with the power and computing resources to support multi-arm telemanipulator systems to be attached to the vehicle's large front panel. It will be interfaced to the vehicles multi-processor computer system which is equipped to support three high-performance microprocessor systems enjoying high-speed communication with one another and with the teleoperator control station. These resources will support high-quality teleoperation research using manipulator systems currently in development. Although the processors being used are IBM-PC compatible units (which permits inexpensive purchase of excellent processing power), the IBP PC operating system has been discarded inf favor of QNX, a real-time, multiprocessor, multitasking operating system sold by Quantum Software of Canada. This operating system has made it extremely easy to configure a powerful, flexible computer system with very high-speed (3Mb/sec) interprocessor communication. The vehicle itself has provision for three parallel computer processors, so that it may ultimately perform programmed tasks under vision-based control, with all processing performed on-board and with no control-station connection at all.

LSTAR is uniquely positioned to perform advanced, ambitious research in remote-vehicle teleoperation, maneuvering, and telemanipulation. The Laboratory is committed to advanced teleoperation research, and has demonstrated the technical abilities necessary for developing and operating advanced neutral-buoyancy and virtual-environment simulation systems. With a closely directed focus on the human interface, and on control augmentation systems to aid the human operator, the Laboratory aims at achieving the greatest possible productivity for remote vehicles in the weightless environment, using techniques directly transferable to space.

Bibliography

[1] "Interim Report on the January 1980 M.I.T. Tests at the Marshall Neutral Buoyancy Facility," David L. Akin and Mary L. Bowden, (June 1980).

[2] "Human Body Dynamics During Assembly Tasks in Weightlessness," Mary L. Bowden, (November 1980).

[3] "Design Details of the M.I.T. Personal Underwater Maneuvering Apparatus (PUMA)," David L. Akin, (June 1980).

[4] "Failure Modes and Effects Analysis on the M.I.T. SSL Personal Underwater Maneuvering Apparatus (PUMA)," David L. Akin, (July 1980).

[5] "Hand Held Maneuvering Unit for Underwater Zero-G Simulation," Scott Chandler, (December 1980).

[6] "Design and Development of a Power Gimballed Foot Restraint Unit (Cherry Picker)," Klaus Bach and Guido DeFever, (December 1980).

[7] "Design Details for the M.I.T. Personal Underwater Maneuvering Apparatus Mark II (PUMA Mk II)," David L. Akin.

[8] "Failure Modes and Effects Analysis on the M.I.T. Personal Underwater Maneuvering Apparatus Mark II (PUMA Mk II)," David L. Akin.

[9] "Design Details on the M.I.T. Hand Held Maneuvering Unit (HHMU)," David L. Akin.

[10] "Failure Modes and Effects Analysis on the M.I.T. Hand Held Maneuvering Apparatus (HHMU)", David L. Akin.

[11] "Design Details on the M.I.T. Cherry Picker Unit (CPU)," David L. Akin.

[12] "Failure Modes and Effects Analysis on the M.I.T. Cherry Picker Unit (CPU)," David L. Akin.

[13] "NB-32B Test Report: July 1980 SSL Tests at the Marshall Neutral Buoyancy Facility," Mary L. Bowden.

[14] "Assembly of Large Space Structures: Simulation in Neutral Buoyancy and Parabolic Flight," David L. Akin and Mary L. Bowden, (AIAA Conference of Space Platforms, San Diego), (February 1981).

[15] "Dynamics of Manual Assembly of Large Space Structures in Weightlessness," Mary L. Bowden, (M.S. Thesis), (January 1981).

[16] "MIT Space Systems Lab KC-135 Tests - Final Report," Mary L. Bowden (January 1981).

[17] "Quick Look Test Report: NB-42, Neutral Buoyancy Simulation of EVA assemble," Mary L. Bowden, (under NASA Grant NAGW-21), (March 1981).

[18] "Time and Motion Data from NB-32 and NB-32B M.I.T. Tests at Marshall Neutral Buoyancy Facility," Mary L. Bowden and Dawn C. Jegley.

[19] "Strain Gage Data from NA-32 and NB-32B M.I.T. Tests at Marshall Neutral Buoyancy Facility," Mary L. Bowden and Dawn C. Jegley.

[20] "NB-32 Final Report: January and July 1980 M.I.T. Tests at Marshall Neutral Buoyancy Facility," Mary L. Bowden, ed.

[21] "NB-42B Test Report: Neutral Buoyancy Simulation of EVA Assemble," Mary L. Bowden and David L. Akin, (August 1981).

[22] "A Stabilized Six-Degree-of-Freedom Personal Underwater Maneuvering Apparatus," Michel A. Floyd, (M.S. Thesis), (June 1981).

[23] "NB-42 Neutral Buoyancy Simulation of EVA Assembly - Final Report," George L. Sarver III, et. al., (NASA Grant NAGW-21), (December 1981).

[24] "Investigation of the Effect of Duct Configuration on Shrouded Propellers," Susan Elizabeth Flint, (NASA Grant NAGW-21), (June 1981).

[25] "Manufacture and Evaluation of a Head-Up Display," Sarah A. Gavit, (Presented at the Regional AIAA Student Conference, (April 1982).

[26] "Design, Fabrication and Testing of a Rotating Foot Restraint," Dawn Jegley and Vicki Schreer, (May 1982).

[27] "Learning Evaluation for the Use of NASA Foot Restraints," Kim M. Lewis, (May 1982).

[28] "A Time and Motion Study of the Assembly of Simulates Space Structures," Dawn C. Jegley, (March 1982).

[29] "Failure Modes and Effects Analysis of the M.I.T. Minimanipulator," D.L. Akin, (December 1982).

[30] "Proceedings for the NASA/MIT Colloquium on Manual Assembly of Large Space Structures," D.L. Akin and Mary L. Bowden, (May 1982).

[31] "EVA Capabilities for the Assembly of Large Space Structures," D.L. Akin and M.L. Bowden, (IAF #82-393), (September 1982).

[32] "Time and Motion Study , June 1981 Tests (NB-42B)," Dawn Jegley, (April 27, 1983).

[33] "Design and Testing of an Advanced Space Suit Glove," Mitch Clapp, (NASA Grant NAGW-21) ,(May 23, 1983).

[34] "Design, Analysis, and Development: The Skinsuit Glove," Mitch Clapp, (August, 1983).

[35] "Beam Assembly Teleoperator (BAT): Design Data Book," J. Spofford et al., (NASA Grant NAGW-21).

[36] "Beam Assembly Teleoperator (BAT): Failure Modes and Effects Analysis," J. Spofford et. al., (NASA Grant NAGW-21).

[37] "Design and Control, of a Beam Assembly Teleoperator," E.B. Shain, (S.M. Thesis) (NASA Contract NAGW-21), (May 1983).

[38] "Preliminary Correlation of the STS-6 EVA with Neutral Buoyancy Training Activity," D. Akin and M. Bowden, (NASA Contract NAGW-21), (July 12, 1983).

[39] "Facilities Operating Procedures for the MIT Space Systems Laboratory Neutral Buoyancy Personal Video Camera," (NASA Grant NAGW-21), (July 1983).

[40] "Standard Operating Procedures for the MIT Space Systems Laboratory Neutral Buoyancy Personal Video Camera," (NASA Grant NAGW-21), (July 18, 1983).

[41] "Duct Testing: Search for an Improved Neutral Buoyancy Propulsion System," Michael P. Scardera, (NASA Grant NAGW-21), (May 1983).

[42] "Application of Model-Referenced Adaptive Control to Beam Assembly Teleoperator," Catherine Rotival, (June 1983).

[43] "NB-50C Test Plan Structural Assembly Demonstration Experiment, November 1983," D.L. Akin, et. al., (NASA Contract NAS8-34501), (October 12, 1983).

[44] "Structural Testing of the Langley Connector," Mary L. Bowden, (NASA Grant NAGW-21), (October 15, 1983).

[45] "Preliminary EASE Experiment Requirements," David L. Akin, (NASA Grant NAS8-35608), (October 20, 1983).

[46] "Standard Operating Procedures for the M.I.T. Beam Assembly Teleoperator," John Spofford, (NASA Contract NAGW-21).

[47] "Facilities Operating Procedure for the M.I.T. Beam Assembly Teleoperator," John Spofford, (NASA Contract NAGW-21).

[48] "Neutral Buoyancy Test Plan: NB-53C/N858A," David L. Akin, (under HQ grant and EASE), (January 1983).

[49] "Spacecraft Trajectory Targeting by Boundary-Condition Orbit Fitting," Dale G. Stuart, (June 1984).

[50] "Dynamics and control for Free-Flying Robots in Zero-Gravity," John R. Spofford, (NASA Grant NAGW-21), (June 1984).

[51] "NB-53D Test Plan - Neutral Buoyancy Simulation of Manual and Remote Proximity Operations," David L. Akin, (August 1984).

[52] "NB-50D Test Plan - Structural Assembly and Deployment Experiment," David L. Akin, (July 1984).

[53] "Experimental Assembly of Structures in EVA Requirement Document," David L. Akin, (August 1984).

[54] "NB-58C Test Plan - Experimental Assembly of Structures in EVA," David L. Akin, (October 1984).

[55] "EVA Analysis Techniques," Daniel Cousins and David Akin, (February 1985).

[56] "Telepresence Systems: Analysis and Neutral Buoyancy Verification," David L. Akin, (NASA Grant #NAGW-21), (February 17, 1985).

[57] "A Digital Control System for an Underwater Space Simulation Vehicle Using Rate Gyro Feedback," Gary G. Vyhnalek, (NASA Grant #NAGW-21), (May 10, 1985).

[58] "An Economic Analysis of Humans and Teleoperators for Space Construction," David G. Stuart, (October 1985).

[59] "8 PSI Spacesuit Glove Design Project Final Report," David Akin, Robert S. Wolf, Adam R. Brody, (May 1985).

[60] "Supervisory Control of the Right Arm of the Beam Assembly Teleoperator," Anthony J. Manganiello, (NASA Grant NAGW-21), (June 1985).

[61] "Quarterly Report of the Space Operations Research Group Space Systems Laboratory, M.I.T.," David L. Akin, (NASA Grant NAGW-21), (February 20, 1986).

[62] "Parametric Testing of Space Teleoperators through Neutral Buoyancy Simulations," David L. Akin, (NASA Grant #NAGW-21), (April 1986).

[63] "NB-53E Test Plan Experimental Investigation of EVA, Teleoperation, and Robotics for Space Operations," David L. Akin, (NASA Grant NAGW-21), (March 20, 1986).

[64] "Design and Testing of a Head Mounted Control Device," John Robert Apgar, (NASA Grant NAGW-21), (June 1986).

[65] "Design of an Interface for a Space Teleoperator Manipulator Arm," Bruce Michael Schena, (NASA Grant NAGW-21), (June 1986).

[66] "A Systems Analysis of Humans and Machines in Space Activities," David G. Stuart, (partially funded by NASA Grant NAGW-21), (June 1985).

[67] "The Instrumented Beam System", Dan Cousins, (NASA Contract #NAGW-21), (October 1986).

[68] "Optimal Force Distribution for Two-Arm Transport of a Payload in Zero Gravity", Craig R. Carignan, D.L. Akin, (NASA Research Contract #NAGW-21), (October 1986).

[69] "3-D Position and Attitude Measurement for Underwater Vehicles," John Spofford, (NASA Grant NAGW-21), (December 29, 1986).

[70] "Beam Assembly Teleoperator: Coordinates and Kinematics," John Spofford, (NASA Grant NAGW-21), (April 10, 1987).

[71] "Spacecraft Flight Simulation: A Human Factors Investigation into the Man-machine Interface Between an Astronaut and a Spacecraft Performing Docking Maneuvers and other Proximity Operations," Adam Randall Brody, (April 1987).

[72] "Human Factors Issues in Space Station Operations," David L. Akin, (NASA Grant #NAGW-21), (March 1987).

[73] "NB-67B Neutral Buoyancy Simulation of Teleoperation EVA Anthropometrics," Space Systems Laboratory, (NASA Grant #NAGW-21), (May 1987).

[74] "Scuba and KC-135 Test Results Biomechanics of Manuel Handling Tasks," D. Cousins, (NASA Contract #NAS9-17266), (June 1987).

[75] "Biomechanics of Extravehicular Activity and its Neutral Buoyancy Simulation," D. Cousins, (NASA Contracts NAS8-35996, and NAS9-17266), (June 1987).

[76] "Attitude Sensor: Design Documentation and User's Guide," Joe C. Parrish, (under NASA Grant #NAGW-21), (August 1987).

[77] "Towtest System" Design Documentation and User's Guide," Joe C. Parrish, (under NASA Grant #NAGW-21), (August 1987).

[78] "Trajectory Control of Free-Flying Space and Underwater Vehicles," Joe C. Parrish, (Under NASA Grant #NAGW-21), (August 1987).

[79] "Optimization of Manual Control Dynamics for Space Telemanipulation: Impedance Control of a Force Reflecting Hand Controller," Justin David Billot Paines, (Under NASA Grant NAGW-21, NASA Contract NAS 9-17266), (August 1987).

[80] "Control Strategies for Manipulating Payloads in Weightlessness with a Free-Flying Robot," Craig R. Carignan, (Under NASA Grant #NAGW-21), (September 1987).

[81] "Attitude Control and Human Factor Issues in the Maneuvering of an Underwater Space Simulation Vehicle," Janice Marie Tarrant, (under NASA Grant NAGW-21), (August 1987).

[82] "Human Operator Performance in Dynamic Multi-Task Environments," Antonio Marra Jr., (NASA Grant #NAGW-21), (February 1988).

[83] "Time and Resource Constrained Scheduling with Applications to Space Station Planning," Clifford Roger Kurtzman, (Under NASA Grant NAGW-21), (February 1988).

[84] "Artificial Intelligence Applications in Teleoperated Robotic Assembly of the Ease Space Structure," Herbert E.M. Viggh, (under NASA Grant #NAGW-21), (February 1988).

[85] "Biomechanics of Extravehicular Activity and Neutral Buoyancy Simulation," Daniel Cousins, David L. Akin, Justin D.P. Paines, Mary L. Bowden, NASA Johnson Space Center, (March 31, 1988).

[86] "Supervisory Control Algorithms for Telerobotic Space Structure Assembly," David Elliott Anderson, (Under NASA Grant #NAGW-21), (May 6, 1988).

[87] "Coordinated Control of a Free-Flying Teleoperator," John Spofford, (Under NASA Grant NAGW-21), (May 1988).

[88] "Manipulator Control with Obstacle Avoidance Using Local Guidance," Koichi Funaya, (Under NASA Grant #NAGW-21), (August 1988).

[89] "Effects of Stereovision and Graphics Overlay on a Teleoperator Docking Task," Vicky M. Rowley, (September 1989).

[90] "Applications of a Three-Dimensional Position and Attitude Sensing System for Neutral Buoyancy Space Simulation," Karl G. Kowalski, (October 1989).

[91] "Guide to Operations and Systems: Apparatus for Space Telerobotic Operations (ASTRO)," Wendy. M. Power, (March 1990).

[92] "Closed-Loop Depth and Attitude Control of an Underwater Telerobotic Vehicle," Wendy M. Power, (March 1990).

[93] "Design and Implementation of a Multiprocessor System for Positions and Attitude Control of an Underwater Robotic Vehicle," Ella M. Atkins, (May 1990).

[94] "Design and Testing of a Stewart Platform Augmented Manipulator for Space Applications," Terrence W. Fong, (May 1990).

[95] "Experimental Modeling of EVA Task and Workload Using Force-Torque Sensing Apparatus," Sayan Chakraborty, (July 1990).

[96] "Joint and Actuator Design for Enhanced Stability in Robotic Force Control," Russell D. Howard, (August 1990).

[97] Implementation of of Distributed Processing for the Beam Assembly Teleoperator," Judson C. Hedgecock, (August 1990).