EFFECTS OF STEREOVISION AND GRAPHICS OVERLAY ON A TELEOPERATOR DOCKING TASK

by

VICKY MARIE ROWLEY

S.B. Massachusetts Institute of Technology (1989)

Submitted to the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements of the Degree of Master of Science in Aeronautics and Astronautics

at the

Massachusetts Institute of Technology

September 1989

© Massachusetts Institute of Technology 1989
All rights reserved

Signature of Author

Certified by Professor David L. Akin
Thesis Supervisor

Accepted by

Professor Harold Y. Wachman
Chairman, Departmental Graduate Committee
EFFECTS OF STEREOVISION AND GRAPHICS OVERLAY
ON A TELEOPERATOR DOCKING TASK

by

VICKY MARIE ROWLEY

Submitted to the Department of Aeronautics
on August 12, 1989 in partial fulfillment of the
requirements for the Degree of Master of Science

ABSTRACT

The hardware and software necessary to operate the Multimode Proximity Operations Device (MPOD) - a submersible, telerobotic vehicle - in closed-loop attitude hold mode, with a graphics display indicating position and attitude superimposed over either monoscopic or stereoscopic video feedback from the vehicle, were designed, implemented, and evaluated in a neutral buoyancy simulation of a zero gravity environment. The completed system was used in a teleoperated docking task, and performance of the task was evaluated for each of four cases: 1) monovision only, 2) monovision with graphics overlay, 3) stereovision only, and 4) stereovision with graphics overlay.

The onboard control system utilized input from the operator, as well as feedback from pendulum inclinometers and rate gyros onboard the vehicle, to control the thrusters responsible for translation and rotation of the vehicle.

Position and attitude of the vehicle were determined using a combination of data from the pendulum inclinometers, and data from a three dimensional acoustic positioning system (3DAPS). Once determined, this information was graphically displayed and superimposed upon the video signal transmitted from the vehicle using a Macintosh II computer system. The video signal was generated by two cameras mounted side-by-side onboard the vehicle. Alternate fields from each of the two cameras were displayed on the main monitor of the control station. A stereoscopic effect was produced by using LCD shutters to present the view from a given camera to the appropriate eye. For monovision, video from one of the two cameras was used independently.

Once operation of the control system proved satisfactory, four test subjects, two experienced and two inexperienced, were tested a number of times in each of the four test cases listed above. These tests involved flying the MPOD from an initial point to a target, and then docking the vehicle with the target.

Quantitative results of the test subjects' performance indicated that the presence of the graphics overlay reduced the average time required to dock the vehicle an average of 15% in cases using monovision, and 19% in cases using stereovision. At each data point, the distance from the vehicle's center to the optimal trajectory line extending straight back from the target was calculated. For each test run, these calculated distances were averaged to produce an average trajectory error for that run. Results of this analysis were inconclusive. The use of stereovision made little difference on the performance of the trained test subjects. Results were contradictory between the untrained subjects concerning the use of stereovision.

Thesis Supervisor: David L. Akin
Assistant Professor of Aeronautics and Astronautics
DEDICATION

This thesis is dedicated to my mother who encouraged me, supported me, loved me, and was always there for me through twenty-four of the hardest, most wonderful years of my life.

ACKNOWLEDGEMENTS

I would like to thank Dave Akin for having the vision to shape the Space System Laboratory the way he has, for sharing his expertise in moments of crisis, and for allowing me to pursue a thesis which truly interested me. Very special thanks and acknowledgment go to Ella Marie Atkins. I will be eternally grateful for her support and friendship. Without her selfless attitude toward the use of MPOD and her continual support and maintenance of that vehicle, this research would not have been possible. More importantly, she has been my friend, sharing everything from her dragon to her technical drawings, sitting with me through lengthy, detailed discussions of "extracurricular activities", and making it infinitely easier to keep tabs on Lieutenant Smith. Karl Kowalski deserves recognition for most graciously allowing my use of the 3DAPS system under his care, and many thanks to him, to Matt Machlis, and to Max, who devoted innumerable hours to the supervision and improvement of that system. I would like to acknowledge Robert M. Sanner for his development of the PiVeCS communications system used with MPOD and RECS, and for his work in the development of the closed loop control system for MPOD. Although it is not possible to properly recognize each of the many people from the SSL who have assisted and inspired me, I would like to thank the following: Lisa K. Evelsizer, the other half of the Dynamic MPOD Duo and a water goddess; Wisdom Coleman, Paul Duncan, Karl VonEllenreider, and the many other people who provided scuba support; all the inhabitants, of room 33-407, past and present; and the invaluable UROP students who provided the manpower necessary to support this type of testing.

Finally, special thanks to the many friends who helped me through the fun times and the hard ones: Russell Howard who helped make this past year my favorite at MIT; Ella Atkins, Sue Levene, and Alexe Page who continually inspire me to be better and do more; the members of the MIT Alumni Pistol Team (you guys know who you are) who are always there to abuse me whether I need it or not, especially Spencer, Jon, and Duncan who helped me to proofread this document; and Jon Mark Williams who is always willing to share his electronic and mechanical hardware (for a price).

This work was supported by the NASA Office of Aeronautics and Space Technology, under NASA Grant NAGW-21.
**Introduction**

The economic viability and success of any attempt at space industrialization is directly related to the level of productivity realized. Consequently, there is much interest in the accurate prediction, quantification and augmentation of human productivity levels in the space environment. To this end, the MIT Space Systems Laboratory (SSL) began investigating human factors and the use of telerobotics in space operations in 1978. Since that time, a number of studies and experiments have been completed in an effort to clarify and define man's capabilities and limitations in a zero-gravity environment, as well as to find methods which might improve his effectiveness.

To investigate the effects of a zero-gravity environment, the SSL uses a technique known as "neutral buoyancy simulation." As the name implies, neutral buoyancy simulation uses water's natural buoyancy to eliminate the apparent effects of gravity on an object. Neutral buoyancy methods of space simulation are used for several reasons. They are significantly less expensive and more accessible than actual testing in orbit, permitting a greater number of tests to be run more frequently. They are easier to schedule, less costly, and less time-constrained than simulations performed in a KC-135 aircraft, allowing longer tests to be performed. Furthermore, neutral buoyancy simulations allow the use of sensors such as pendulum inclinometers and hydrophones which would be inoperable in space because they depend on the presence of gravitational forces and atmospheric conditions unavailable in orbit. These sensors provide a comparatively inexpensive source of position and attitude information relative to the inertial instruments necessary for space operations.

In support of telerobotics and human factors research, the SSL has developed three submersible, prototype, telerobotic vehicles. Through the use of these vehicles in neutral buoyancy simulations, experience and information has been acquired which will contribute to the successful future development of similar vehicles designed to assist in space operations. These simulations have identified a continually expanding range of applications and abilities for
such vehicles, subsequently increasing their potential utility in space. Uses demonstrated in the SSL include aiding in the construction of space structures, and the engagement and transport of humans and materials. Also, information from the testing and evaluation of equipment used during these simulations will be incorporated to advance the design of similar equipment for use in space.

Increasing the potential for robotics applications in space and promoting the development of better hardware is only one way in which the primary goal of increased human productivity in space may be achieved. The SSL also strives to increase the capacity for humans in space by investigating ways in which the human operator can function more effectively. In much the same way that telerobotics research looks at ways to improve the performance of telerobotic equipment, human factors research looks at ways to improve the performance of the human operator of that equipment.

A number of factors can affect human performance in a task such as controlling a telerobotic vehicle. Some of these factors, such as emotional state and physical condition of the subject, are difficult (if not impossible) to control. Others factors, specifically the content and form of the information presented to the operator from the vehicle, and the means by which the operator transmits control outputs to the vehicle, can be controlled, and can have a significant impact on task performance. During a telerobotic space operation, the operator of the vehicle is responsible for processing a wide variety of informational inputs, and producing an output command which affects the desired action. During a typical task, such as docking the vehicle with a target, for example, the pilot would be responsible for determining the vehicle's position and attitude relative to the target, and for maneuvering the vehicle so that it properly engages the target.

In order to perform such a task, the operator must have sufficient information to discern his attitude and position. One way to provide this feedback is with video images transmitted
from one or more cameras located in or around the vehicle. However, this particular form of video feedback, while sufficient for completion of the task, may be very difficult to interpret under certain conditions. This sort of limitation on the feedback to the operator directly increases the amount of time required to complete the task.

One solution to this problem is to increase the amount of information flowing to the operator. Many sources of feedback could be used to augment the conventional monoscopic visual feedback from the vehicle. For example, data from onboard sensors could be used to provide angle and angle rate information which is displayed for reference by the operator, or a stereoscopic vision system could be used to supply added depth perception. Unfortunately, simply increasing the amount of feedback available to the operator could actually have an adverse effect on his performance. If the rate or quantity of the data provided to the operator exceeds his ability to interpret and act on that data, confusion and decreased performance result. The challenge becomes to present no more information than necessary to the operator, and to use a clear, concise method of displaying that information. This is the problem which was addressed in the research described below.

Project Scope

All three of the teleoperators in the SSL were equipped with onboard cameras which transmitted real-time video feedback to the operator at the surface. However, the video signal did not always contain information sufficient for rapid, absolute determination of the vehicle's attitude or position. If the vehicle was near an object which took up a significant portion of the video image, references in the background normally used to determine position and attitude became unavailable. For example, in the case of docking a teleoperator with a target it became difficult to distinguish between errors in pitch and errors in altitude near the target because angle information in the video image decreases as the target begins to dominate the operators field of view, obscuring other sources of attitude information.
Real-time information concerning the position and attitude of the vehicle can be made available through sources other than video, however. An acoustic measurement system independently developed in the SSL was adapted for just this purpose. By using this system, either alone or in conjunction with other available sensors, and transmitting the resulting information to the control station, the vehicle's position and attitude relative to an absolute reference could always be available to the operator.

The question arises of how to convey this information to the operator in the most concise, understandable manner. A straight-forward textual display, while concise, is not necessarily easy to interpret. By converting this information into a two-dimensional graphical display, one step of the data interpretation task was effectively eliminated for the operator. Furthermore, by superimposing these graphics images on the video display from the vehicle, the operator was not forced to shift his attention to a separate display in order to reference the additional information.

By integrating one of the teleoperators with an underwater, acoustic positioning system, it became possible to superimpose such a graphics overlay, indicating position and attitude, on either the monoscopic or stereoscopic real-time video display from the teleoperated vehicle. This project examined the effects of such a graphics overlay on the conventional video feedback from a single onboard camera. In addition, the effects of the same overlay on a stereoscopic display from two cameras mounted side-by-side were also investigated. Performance was evaluated both by measuring the time required to complete the task, and by comparing the actual trajectory of the vehicle during the task to the nominal trajectory extending straight back from the target. Background information on the equipment used in this research is given below.
Background

Multimode Proximity Operations Device

The vehicle used in this investigation was the Multimode Proximity Operations Device (MPOD)[1]. MPOD is one of three, six-degree-of-freedom, submersible vehicles used for robotics research in the SSL. It was chosen because of its ability to approach and engage a docking target, and because information from its onboard sensors could provide accurate, near real-time data on the vehicle roll and pitch angles. The angle information came from a set of three orthogonally oriented pendulum inclinometers whose accuracy depended on the degree of orthogonality between the local gravity vector and the individual pendulum's axis of rotation. Readings from the pendulum rotating about the axis most near the gravity vector were generally unreliable. Consequently, when the vehicle was flown in a straight and level attitude, as it was for these experiments, the information from the pendulum rotating about the yaw axis was unreliable and was not used.

MPOD had three possible modes of operation: onboard, direct-view, and teleoperation. Only the latter was relevant in these tests. Teleoperation is the operation of a vehicle such as MPOD from a control station removed from the worksite. In this mode, MPOD's onboard computer system transmitted information and received commands from the operator via a dual channel fiber optics link to the control station on the surface. Onboard control input devices, such as the hand controllers shown in figure 2, were not used, and the only source of visual feedback to the operator was from a video signal relayed from a camera, or cameras, onboard the vehicle.
MPOD could be flown in both open- and closed-loop control configurations. The default configuration was open-loop mode, in which hand controller movement by the operator was the sole source of control input to the vehicle. The closed-loop control system, which was implemented in the onboard computer, was engaged or disengaged by pressing a button on the rotational hand controller. The purpose of this system was to stabilize the vehicle's attitude using information from sensors onboard the vehicle.
MPOD Hardware

MPOD was constructed from fiberglass-reinforced structural foam panels mounted on an aluminum frame. The vehicle's orientation and position were controlled by three pairs of orthogonally-located propeller/thrusters which were powered by six eighteen-volt battery packs located in the left and right sides of the vehicle. The voltage from these battery packs was switched through a power relay controlled by a pneumatic solenoid. Figures 1 and 2 show the
orientation of the thrusters, as well as the coordinate system used in control system implementation, and graphics overlay generation.

Figure 3. MPOD Docking Probe

MPOD was also equipped with a docking probe used to engage docking targets such as satellite mockups. The core of the docking probe was an aluminum cylinder sized to fit inside the tapered hole of the docking target drogue. During docking of the vehicle with the target,
the probe was inserted into this drogue, and, as the tip emerged from the opposite side, three spring-loaded latches hook onto the target back. To rigidize contact between the vehicle and the target, a conically shaped section on the docking probe extended into the docking target drogue. When extended, this section prevented the target from slipping off the latches. It was referred to as the ram. The ram and the aluminum latches at the tip of the probe were pneumatically actuated, and were controlled by buttons on the rotational hand controller. To disengage the vehicle from the target, the ram was retracted, and the latches were released. The vehicle was then free to move away. The pneumatic solenoids were used to actuate the power relay, the ram, and the latches on the docking probe. These solenoids were powered by an onboard pressurization system incorporating three scuba tanks. This system of scuba tanks also supplied pressurized air to the battery boxes and electronic systems to prevent damage from water leakage. Figure 2 shows a top view of MPOD.

Another essential part of MPOD's hardware, which is not shown in figure 2, was the control box, located near the center of the vehicle. This box contained the computer system and electronics which were effectively the brain of MPOD. It also held the onboard sensors used to supply feedback information to the onboard control system. This included a three-axis gyro package[1] and three orthogonally oriented pendulum inclinometers[2]. The control battery packs used to supply power to these systems were located below the aft scuba tank.

**MPOD Electronics**

MPOD's latest onboard computer system included an AMPRO Little Board/PC™ singleboard microcomputer (V40 processor - 8086 compatible), complete with a 3 -1/2" disk drive. This system exchanged information with the computer system on the surface and interpreted the incoming information to produce the appropriate control signals for MPOD's various subsystems. The onboard computer system's control of MPOD may be separated into two basic functions. First is control of the thrusters. A proportional output from the thrusters
was achieved by varying the duty cycle of the applied power. The onboard computer system was responsible for determining the appropriate duty cycle and direction signal for each of the six thruster pairs as a function of input from the operator and control system. Once determined, these values were supplied to the pulse width modulation unit which generates the signal controlling the output of the thrusters. The second function of the control system is control of the solenoids which activated the power relay, ram, and docking probe latches.

Three-Dimensional Acoustic Positioning System

In conjunction with teleoperator development and operation, the SSL has developed the 3-Dimensional Acoustic Positioning System (3DAPS)[3][4]. The 3DAPS system was conceived as a method by which the position and/or attitude of an object being tested underwater could be determined unambiguously using acoustic sensors. Although it was possible to use other methods, such as inertial instruments, rate gyroscopes and/or inclinometers to obtain this information, the 3DAPS system was chosen for its relatively low cost, its accuracy in all six degrees of freedom, and its large, well-defined area of operation.

Using eight fixed acoustic emitters, 3DAPS determined the position of a hydrophone by timing the propagation delays of acoustic pulses from the emitters through the water to the hydrophones. By rigidly fixing four hydrophones in a known configuration on a vehicle (for example), the position and attitude of the vehicle was calculated using standard coordinate transformation methods[5]. To accomplish this, a controlling sequencer located at the surface repeatedly fired the emitters in sequence. Each time an emitter was fired, the sequencer also sent a timing signal to a receiver onboard the vehicle, which started a counter for each hydrophone. The signals from the hydrophones were also connected to this receiver. When the signal from a hydrophone indicated that it had received the pulse from an emitter, the counter corresponding to that hydrophone was stopped. The receiver used the measured time of these delays to calculate the equivalent ranges based on the speed of sound in water and the
last known positions of the hydrophones. The last position information was used to filter the effects of erroneous hydrophone readings resulting from reflection or blockage of the signal from an emitter. The calculated ranges were then transmitted to the operating computer. This cycle was repeated approximately every two seconds. A block diagram of the entire 3DAPS system is shown in figure 5.

The coordinate system used by 3DAPS for this research was defined by three edges of the cube in which it operated. The emitters may be arranged in any convenient configuration around the boundaries of the desired test area. The cubical arrangement used here was chosen because it simplified the computations and was easy to establish. In this arrangement, the surface of the water defined the z=0 plane, with the positive z-axis pointed down. The x- and y-axes were arranged according to the right-hand-rule along the edges of the pool. The emitters were set up at the corners of this cube in positions defined relative to the described 3DAPS coordinate system. The hydrophone positions were also calculated using this coordinate system. A typical 3DAPS system arrangement is shown below in figure 4.

Figure 4. 3DAPS Setup (H=hydrophone, E=emitter).
Figure 5. 3DAPS Block Diagram

(from Spofford, J.R., "3-D Position and Attitude Measurement for Underwater Vehicles", SSL Report #21-86)
Control Station Development and System Integration

Reconfigurable Experimental Control Station

Before the complete experiment could be performed, the individual systems and equipment involved had to be integrated. The control station created to accomplish this was the Reconfigurable Experimental Control Station (RECS)[6]. To facilitate this experiment, and others in the future, RECS was designed from the beginning to be flexible and to allow variation and expansion. Most of the equipment and features of RECS were chosen and developed to be modular in design to permit easy upgrading and/or substitution of equipment when necessary. The philosophy and ultimate objectives for the design and development of RECS are introduced below.

The first guideline for RECS development came from the most severe limitation of the Integrated Control Station (ICS), a previously developed control station used to control the Beam Assembly Teleoperator (BAT), another of the SSL's teleoperators. Utilization of ICS with BAT provided invaluable experience which guided the design and construction of RECS, and inspired the desire to surpass the limitations inherent in the design of the previous control station. Although, like RECS, ICS was a fully equipped control station with multiple monitors and controls which could be used in the teleoperation of any of the three vehicles, it was designed specifically for BAT. To use the computer equipment and controls of ICS with a teleoperator other than BAT would have required extensive modifications to be made in either the control station or the vehicle. Originally, when there was only one teleoperator in existence in the SSL, this was not a problem. As the second and third teleoperators came into being, however, the need arose for an additional, fully-equipped control station which was flexible enough to interface quickly, easily, and reliably with any of the three existing teleoperators, as well as with future teleoperators and the Silicon Graphics IRIS computer system used in computer simulations of space operations. In RECS, this flexibility was achieved through use of the standard RS-232 serial port of an IBM computer system to effect communications with
other systems. By comparison, ICS used a heavily customized communications scheme unique to ICS and its teleoperator, while RECS used a standard for serial communications which was supported by numerous other commercially available systems.

Also aimed toward the goal of general flexibility was the configuration of the controlling software on RECS. General routines, written in the "C" programming language, existed for determining the state of any individual input device. The particular application or driver was then free to interpret that information and initiate the appropriate response. In addition to the controlling IBM computer system used to effect communications and to interface the various peripheral input devices on RECS, there was a Macintosh II computer system available. The Macintosh II was used for data acquisition, for graphics generation, or as a remote terminal for the Silicon Graphics IRIS.

Further guidelines for the physical layout of RECS came from the desire to create a more authentic space workstation environment. To begin, hand controllers like those used in the space shuttle were chosen and installed in the center control panel of RECS. Each hand controller commanded three degrees-of-freedom with the translational hand controller moving forward and backward for x-translations, right and left for y-translations, and up and down for z-translations. The three rotational degrees-of-freedom were controlled by rocking the rotational hand controller forward and backward for pitch, right and left for roll, and by twisting the hand controller on its base to control yaw.

To further model RECS as a space station work environment, it was designed with its display monitors and controls in a wrap-around style. The monitors were positioned with a twenty-five inch Sony color monitor used for the main screen display centrally located immediately in front of the operator. Four nine inch monitors were for the controlling computer screen and for supplementary video images from other sources were located to the
operator's left. An NEC Multisync II® monitor to the operator's right was used to display NTSC formatted video signals and/or the output from the Macintosh II computer system.

The design of RECS was also driven by the development of new technologies which could be used to transfer information between the operator and the control station, or between the control station and vehicle being flown. One example of this was the communications link between the control station and the vehicle. ICS communicated with BAT using conventional coaxial cable. Drawbacks to the use of this cable included weight, water drag, and the fact that, because it was an electrical signal, it had to be sealed against contact with water at all times. RECS took advantage of the developments in fiber optic communications by using a dual channel fiber optics cable to exchange information with a teleoperator. Not only was this cable thinner and lighter than coaxial cable, but more importantly, when the cable became damaged during a simulation, it was replaced with no adverse effect while the vehicle remained submerged, simply by disconnecting the damaged cable and substituting a replacement.

Another new technology implemented on RECS was the nine inch touch screen mounted over one of the nine inch color monitors. The monitor may be used to display any NTSC formatted video signal, either from a camera or computer system. Typically, it displayed computer-generated text and graphics to which the operator responded by touching an appropriate spot on the screen.

The programmable display push buttons and trackball, mounted in the center control console, were other new technologies of which RECS took advantage. Because these buttons were software programmable, they could be used as one, two, three, or four individual button(s). The display on these buttons, generated by independently lit pixels, was also software programmable. When an event occurred which altered either the function of a particular button or the state of the object it controls, this change was reflected on the display of that button. This allowed greater flexibility, reduced the total number of buttons required, and
made the control panel less cluttered. Also, the display could include both conventional text and customized graphics with the only limit being the number of pixels available. This feature could be used to make the buttons even easier to understand, especially in applications where their function periodically changed.

There was one more important feature which was common to both ICS and RECS. Both were completely mobile with minimum disassembly. The necessary equipment associated with each control station was installed in an aluminum frame bolted to a four-wheeled cart. This was done because the equipment was frequently transported between the laboratory used during development, and the swimming pool used for testing. The RECS cart utilized pneumatic tires, and a steering handle. Experience with ICS indicated these features would be desirable to reduce shock which could damage the electronic equipment and to generally make the task of transporting the equipment easier. The layout of RECS is shown in figure 6.
Figure 6. RECS layout.
Figure 7. RECS block diagram

- MPOD
- Serial Port #1
- MAC II for 3DAPS & Graphics
- Serial Port #2
- Controlling IBM AT Computer
- Intel 8255A Programmable Peripheral Interface
- Intel 8255A Programmable Peripheral Interface
- Intel 8255A Programmable Peripheral Interface
- 8X8 Crosspoint Switch
- Video Source
- Monitors
- Trackball Decoding Electronics
- Trackball
- Programmable Display Push Buttons
- Available resources not used
Figure 7 shows a block diagram of the electronics for RECS. The figure includes those systems used during this research as well as features which were not used here but which were available for other applications. The controlling IBM AT computer used for these tests was equipped with only two serial ports. By adding a third serial port, the touch screen and programmable display push buttons could have been implemented, however they were not needed for these tests. They could have been connected to the second serial port if communication with the Macintosh II was unnecessary. Also shown in this figure is the software-controlled video switching unit used to switch input video signals among output devices such as monitors or recorders.

Video System

In order to examine the effect of the graphics overlay both in cases using monoscopic visual feedback and those using stereoscopic visual feedback, a video system capable of switching quickly and easily between both modes of operation was necessary. The SSL had previously developed a stereovision system for use with BAT; unfortunately, time-sharing the existing system would have made it impossible to run simultaneous tests on both MPOD and BAT. This would have resulted in inefficient use of valuable time available for actual neutral buoyancy testing. Furthermore, the system used with BAT employed two cameras placed side by side on the vehicle to produce views which corresponded to binocular vision. By displaying these views on small, individual monitors placed directly in front of the operator's eyes, a stereoscopic effect was achieved. Unfortunately, the required placement of the monitors directly in front of the operator's eyes made it impossible to simultaneously view both the video image from the vehicle, and the controls and informational displays of the control station. These facts, combined with the development of reasonably priced liquid crystal display (LCD) eyeglasses, prompted the decision to design a second stereovision system for use in the SSL.
The second stereovision system was implemented using the main screen of the control station to alternately display video fields from two cameras mounted side-by-side onboard the vehicle. The images transmitted from the right and left cameras were conveyed to the right and left eyes, respectively, using a set of liquid crystal display (LCD) eyeglasses from a SEGA™ video system. The LCD eyeglasses were synchronized with the video signals being transmitted from the two cameras such that, when a field of the video display was being generated by the right camera, the right lens of the eyeglasses became transparent and the left lens opaque. When the next field of video from the left camera was displayed, the state of the lenses reversed.

A simplified schematic diagram of the electronic system used to realize this is shown in figure 8. The square wave signals to the right and left elements of the LCD eyeglasses were 180 degrees out of phase. The common signal supplied to both elements was alternately in phase and 180 degrees out of phase with the square wave for each side, as alternating fields of video were displayed. When the signal for a particular side was in phase with the common signal, no potential difference was seen by the element and it was transparent. As the vertical sync on the video signal triggered the start of the next field and the signals went out of phase, a potential difference was seen which caused the element to become opaque. The necessary difference in potential of 24 volts was obtained by amplifying the left, right, and common signals using amplifiers not depicted in figure 8.

To perform the switching of the video signal for the final display, the electronic system included a high speed analog switch used to alternate between the video signals from the right and left cameras. Also included was a toggle switch used to manually choose either monovision or stereovision. In monovision mode, only the signal from the right camera was displayed. The signal from the left camera, though connected, remained unused.
Figure 8. Stereovision system schematic

[Diagram showing the schematic of a stereovision system, including components such as 400 Hz Clock, Video Sync from Right Camera, Toggle Switch (Stereo/Mono Select), LCD Left, LCD Right, LCD Common, Field, Left + Common, Right + Common, Right Lens Transparent, Left Lens Opaque, Left Lens Transparent, Right Lens Opaque, Output Video Signal, and RCA CD4053 High Speed Analog Switch.]
There were both advantages and disadvantages to a system such as this. First, revealing only alternating video fields reduced the effective video frame rate to 30 Hz from the usual 60 Hz. This resulted in flicker which was detectable, but not usually objectionable. Second, there was a slight reduction in the resolution of the picture conveyed to either eye which occurred because only one of the two fields which constituted a video frame was ever seen by an eye. These drawbacks were offset, however, by the increased depth perception, which was gained without the obstruction of the operator's view of the computer displays and controls of RECS, and the reduced cost of this system compared to the one requiring two miniature monitors.

The cameras used in this stereovision system were Pulnix TMC-574 mini solid state color cameras. These cameras were chosen for their low light sensitivity, compact size, and external sync genlock capability. Typically, no additional underwater lighting was used during neutral buoyancy testing because the ambient light available was sufficient. Attenuation of this light as it traveled through the water did occur however, making low-light sensitivity a desirable feature. Because MPOD was not designed with a two-camera stereovision system originally in mind, the cameras and their waterproof PVC housing had to be small enough to fit inside the front of MPOD slightly above the docking probe with as little modification to the existing hardware as possible. These cameras, which measured 1.25" x 1.65" x 6.38" including the external sync and genlock units, fulfilled this requirement very well. Finally, the key to success was synchronization of the system. In order to switch rapidly between the signals from the two cameras but still display an entire field from each without discontinuities or loss of information, it had to be possible to synchronize them so that switching occurred during the vertical retrace period for both cameras. The internal genlock unit of the right camera performed the actual synchronization of the output from that camera to the input synchronization signal from the left camera. The external sync capability of the cameras allowed them to be synchronized to any external source, including the composite video signal.
from the other camera. The video signal from the right camera was used to provide the vertical sync pulses used to synchronize the rest of the system, including the LCD eyeglasses. The power, ground, and video signals were exchanged with the surface via two umbilical cables to the control station.

It should be noted that, while studies have shown that stereoacuity improves proportionally with camera separation, practical considerations prevented the camera centers from being separated by more than three or four inches. This distance, which approximates the average interocular distance of humans, did produce an adequate stereoptic effect, however.

**Graphics Generation**

The Macintosh II on RECS was used to control the acoustic positioning system, to generate the graphic display containing information on the vehicle's position and attitude, and to overlay that graphic symbology on the video image from MPOD. To generate the graphics display, information from 3DAPS used to determine the vehicle's translational position and yaw angle, was used in conjunction with angle information from the two reliable pendula onboard MPOD. Originally, only 3DAPS information was to be used; however, information from 3DAPS was transmitted to the Macintosh II from the 3DAPS receiver only every two seconds. By comparison, the pendula information was transmitted from MPOD to RECS, and then relayed from RECS to the Macintosh II approximately every 0.13 seconds. By using information from the onboard pendula, the roll and pitch angles could be updated more frequently and more accurately than if they were derived through the 3DAPS system. More frequent updates of the information to the operator result in better control. Furthermore, while the sources of error in the 3DAPS data included the effects of reflections and blockages of the signal from the emitters, and of loose connections in the system electronics, pendula data were always available and were accurate to within a fraction of a degree for the two reliable axes.
There were two important considerations in the design of the graphics overlay. The first was speed. The 3DAPS system provided hydrophone range information approximately every two seconds. This included a period of time where the operating computer, in this case the Macintosh II, was waiting for new data while the emitters were firing. Because the two second update time was already excessive, the graphics display was updated within the time of this waiting period.

The second consideration was ease of interpretation. The symbols used were intended either to be similar to something with which the operator might be already familiar, or to be something to which he could easily relate the movement of the teleoperator with respect to its target destination. There was also the question of whether the active portion of the display should present the information as the vehicle's position and attitude relative to the target, or whether it should display the position and attitude of the target relative to the vehicle. This situation was similar to that of the seemingly contradictory displays of a turn coordinator and artificial horizon in an aircraft. The difference appeared as the difference between controlling the vehicle so that moving indicators were moved onto a stationary reference (turn coordinator), or so that a stationary reference was moved onto moving target markers (artificial horizon). Initially, moving indicators representing the vehicle were generated so that they moved onto a stationary reference frame as the vehicle docked. However, this movement directly opposed the movement displayed in the video feedback, an effect which was both confusing and disconcerting. Before actual test runs began, the graphics generation scheme was changed so that it reinforced the video signal rather than contradicting it, by providing a reference that remained stationary on the display while markers indicating relative motion of the target were updated each time new position and attitude information was received.

For both these reasons, speed and ease of interpretation, the graphics display was made relatively simple. First, a stationary black reference consisting of a rectangle centered around a
set of crosshairs on a target circle was established. Next, the graphics representing the target's relative position and orientation, which were divided into translational and rotational indicators, were drawn. The amount of displacement of these indicators from their respective positions on the reference frame was proportional to the displacement of the vehicle from a straight and level attitude and from a translational position on a nominal trajectory line extending straight back from the target. The translational position indicators were a set of the four red corners of a rectangle. This rectangle grew larger as the vehicle neared the target, moved up and down as the vehicle moved below and above the target, and moved right and left as the vehicle moved left and right, respectively. Similarly, a set of red crosshairs was used to display attitude information, i.e. positive roll of the vehicle caused the crosshairs to rotate counter-clockwise, pitching down moved the crosshairs up, and yawing left moved the crosshairs to the right. Figure 9 shows an example display for a case where the vehicle was below and to the right of the target, relatively far away. It also shows that the vehicle was pitched up, yawed left, and rolled to its left.

Figure 9. Sample Graphics Display
To overlay these graphic symbols, the video signal received from the vehicle (either stereo or mono) was connected to a special video card inside the Macintosh II. This card converted the information displayed by the Macintosh II into NTSC format, and effectively overlaid it on the input NTSC video signal. This combined output was then displayed on the twenty-five inch Sony monitor, located at the center of the control console.

Some attenuation of the video signal resulted from its passage through the 200 foot umbilical and Macintosh video card. To minimize this problem, testing was performed during daylight hours with a black plastic shroud placed over the operator and control station. Bright daytime sunlight provided a brighter video signal than normal indoor lighting, improving contrast. The shroud contributed to this effect, by reducing the amount of ambient light incident upon the display.

System Integration

One of the first steps was to establish communications between the four computer systems involved in the operation of MPOD, RECS, and 3DAPS. This information exchange, diagrammed in figure 10, was achieved in the following manner. RECS transmitted command signals to MPOD, and received angle, rotation rate, and thruster output information through a standard RS232 serial port on the controlling IBM AT computer system. Angle information from the two reliable, onboard pendulum inclinometers, as well as time correlation data, was then relayed from the IBM AT to the Macintosh II through a second serial port. While the Macintosh II was receiving this information from RECS, it was simultaneously exchanging data with, and overseeing the operation of, 3DAPS. No information was transmitted from the Macintosh II to the IBM.
MPOD Control System

For a given command input, factors such as inertia coupling, water drag, and offset of the center of mass from the center of buoyancy, combined to create a high degree of coupling between MPOD's six degrees of freedom. This made the open loop configuration very difficult to control. It increased the workload for the pilot, and made the precise maneuvering necessary for close proximity operations, such as docking, much more demanding.

In order to prevent these effects from obscuring the effects of the different display modes, and to make a large number of test runs realistically possible, a closed-loop attitude control system utilizing feedback from the onboard pendula and gyros was used. The commanded, or reference angles for this control system were varied using the rotational hand controller. The control system used in these experiments was very similar to previous controllers used for attitude hold on MPOD[7][8]. However, development of a new system was required by the extensive changes to the onboard electronic hardware resulting from MPOD's conversion to the AMPRO microcomputer system. There were several advantages of this
system over the previous one, in which an 80C88 microprocessor controlled MPOD using an assembly language program stored on an 8K EPROM. Most notably, the IBM-compatibility of the new system allowed MPOD's controlling software to be written in the "C" programming language. This made effecting program changes much easier, and removed some of the difficulty involved in the use of assembly language.

In the development of this control system, MPOD was modelled as a simple integrator. This model assumed that water drag on the vehicle was negligible, and that the center of buoyancy was nearly coincident with the center of gravity. Because drag is a function of vehicle profile, MPOD was built in as near a spherical shape as was practical to help reduce drag effects. To reduce the position offset between the center of gravity and the center of buoyancy, movable lead weights were attached to the vehicle in appropriate locations each time it was flown. These weights also served to equalize the gravitational and buoyant forces on the vehicle. This "balancing" of the vehicle was important because any offset in the positions of the centers of gravity and buoyancy resulted in a moment on the vehicle for which the control system had to compensate, and any imbalance in the gravitational and buoyant forces meant that the vehicle had a tendency either to float or to sink. These effects could not be completely eliminated, but they were reduced by balancing the vehicle at the beginning of each test session.

Under these assumptions MPOD was modelled as three orthogonal, non-coupled systems, one system representing each vehicle axis. The resulting equation of motion for a single axis of this simplified system becomes:

\[ \ddot{\Theta} = \frac{\tau}{I} = \frac{M_C}{I} \]

where \( \Theta \) represents the angular acceleration about an axis (roll, pitch, or yaw axis of the vehicle), \( \tau \) represents the torque around the same axis due to the thrusters operating about that
axis, I is the vehicle's moment of inertia for that axis, and $M_C$ is the control moment or torque resulting from control system commands.

![Control System Block Diagram](image)

*Figure 11. Control System Block Diagram*

$$Mc = \text{control moment} \quad I = \text{vehicle inertia} \quad K_p = \text{proportional gain}$$

$$\phi = \text{reliable angle (pitch or roll)} \quad Ki = \text{integral gain}$$

$$\phi_c = \text{command or reference angle} \quad Kd = \text{derivative gain}$$

The control system implementation for these experiments used a proportional-integral feedforward compensator and a derivative feedback loop. Information for calculation of the proportional and integral terms was derived from the two reliable pendula onboard MPOD. The gyro package was used to calculate the derivative term. The block diagram for this controller is shown in figure 11. The control moment above becomes a combination of the proportional, integral, and derivative feedback terms, so the equation of motion becomes:
\[ \ddot{\Theta} = -K_P \Delta \Theta - K_I \Delta \Theta - K_D \dot{\Theta} \]

where \( K_P \) is the proportional gain, \( K_I \) is the integral gain, and \( K_D \) is the derivative gain.

Preliminary gain values were estimated by calculating the proportional and derivative gains required to produce full thruster output when the vehicle angle deviated from the commanded angle by .25 radians, with the vehicle rotating at .25 radians per second. The integral gain was estimated by calculating the integral gain required to produce full thruster output, assuming a constant error of .25 radians had been in existence for one second without any attempts at correction. Appendix A details of the calculation of the initial control gain estimates. The final, experimentally derived gains used during the docking runs were: \( K_P = 1, K_I = 0.03125, \) and \( K_D = 16. \) All actual gains used for evaluation, testing, and use of the control system were powers of two. This was done to speed computation time by allowing right and left bit shifting to replace multiplication and division.

**Limitations on the MPOD Controller**

There were two hardware constraints which affected the performance of the attitude hold system on MPOD. The first of these was the gyro package used to supply rotation rate information to the control system. Due to the age and extensive use of this sensor package, the signal-to-noise ratio had degraded considerably. A deadband was placed on the input to the control system from these sensors to prevent noise spikes on the output from triggering the thrusters, and to allow for drift in the zero point due to fluctuating voltage levels. The effects of the decreased signal-to-noise ratio and additional deadband were most evident in control about the most vertical axis. Proportional and integral feedback from the pendulum inclinometer rotating about that axis was unreliable, making the gyro package the only source of feedback information. As a result, the control system could neither hold angle, nor damp out rotations about that axis as effectively as was hoped. Overall, the control system worked
well for holding the remaining two vehicle angles, however the pilot was primarily responsible
for vehicle heading, with the control system providing assistance in the form of derivative
feedback to damp out uncommanded rotations.

The second constraint involved the coupling of the thruster pairs to produce both
rotation and translation. MPOD's thrusters were arranged such that the two thruster pairs
which controlled translation in the x-direction, also controlled yaw about the z-axis. The two
which controlled y-translation controlled roll about the x-axis, while the two which controlled
z-translation also controlled pitch rotations about the y-axis. Any deviation of the position of
MPOD's center of gravity from the vertical line through its center of buoyancy created a
moment that resulted in an instability. The fact that the centers could not be made exactly
coincident meant the control system had to continually work to control such instabilities. The
coupling of the thrusters meant that using thrust to control a rotation of the vehicle decreased
the maximum amount of thrust available to affect the corresponding translation. Or,
conversely, using a given set of thrusters to translate the vehicle, decreased the effectiveness of
those thrusters in controlling their respective attitude angle.

When the operator commanded a translation and the control system simultaneously
commanded a rotation, the previous control system resolved the problem of contention between
the two thruster pairs around a given axis by reducing both the control system output and the
commanded output. This reduced thruster effectiveness both rotationally and translationally.
The system used in these experiments calculated how much of the available thrust was being
used to control the vehicle rotationally, and used the remaining thrust to perform translations.
Effectively, rotational commands, either from the operator or from the control system, were
given precedence over translational commands from the operator. This made the problem of
thruster coupling most evident when the pilot attempted to translate along the y-axis. Because
MPOD was most difficult to balance around the roll axis, the y-thrusters were used for angular
control at higher thrust levels, a higher percentage of the time, than either the x- or z-thrusters.
The relatively high rotational demands on the y-thrusters meant that relatively little thrust was left available to affect y-translations. The result was agonizingly slow translation in either y-direction.

**Control System Evaluation and Testing**

Before the docking task performance testing began, best control gains were experimentally determined, and the control system as a whole was tested and verified in the MIT Alumni Swimming Pool.* The first test was used to ascertain the extent of the gyro package degradation, and two additional tests were subsequently used to evaluate system performance at various gain settings. For these tests, MPOD was configured without the 3DAPS system, and it was positioned and oriented by an operator using the hand controllers on RECS.

For the first test, MPOD was rolled about its x-axis with full rotational thrust in open loop mode. The maximum roll rate of the vehicle was achieved and maintained for several seconds. The data from this test were used to determine the maximum possible output of the gyro package. MPOD’s approximate, experimentally determined maximum rotation rate about the x-axis was forty degrees per second. At this rate of rotation, the output from the gyro package for that axis was about half what the original specification sheet indicated it should have been. In light of this fact, the original estimates for the derivative gains were increased by a factor of two.

With this revised estimate for the derivative gain implemented, the next test used for evaluation of gain settings was control during translation. For this test, MPOD was translated in the x-, y- and z-directions, while operating in closed-loop mode. This test was also used to

---

* For details of neutral buoyancy test procedures, see appendix D.
demonstrate the ability of the control system to appropriately allocate the available thrust from a set of thrusters between rotational and translational demands.

The last test involved step inputs to the control system. For these tests, once MPOD was properly operating in closed-loop mode, a signal was sent to the control system from RECS indicating that the reference pitch angle of the vehicle should be either incremented or decremented by thirty degrees. Data were taken to determine the response of the vehicle to such an input, including response time and overshoot at several gain settings.

Results of Control System Evaluation and Testing

During performance testing of the closed-loop control system, data were taken on the vehicle's behavior during commanded translations, and on its response to a thirty degree step change in commanded pitch angle at various gain settings. These tests demonstrated the best gain settings to be $K_p = 1$, $K_I = 0.03125$, and $K_D = 16$.

Figure 11 shows the roll angle response of the vehicle with the controller engaged during $x$, $y$, and $z$ translation inputs from the operator. A rotational hand controller input from the operator approximately twenty seconds into the run established the commanded, or reference roll angle at 186 degrees. The controller then held the roll angle within ±4 degrees of this reference during $x$- and $z$-translations. Data indicated that the roll angle was held only to within ten or fifteen degrees of the reference angle during $y$-translations. However, these readings from the roll pendulum are believed to have been affected by limit cycling of the vehicle around the roll axis, which occurred during $y$-translations. There was no such evidence of limit cycling around the other two axes, perhaps due to the damping effects of water drag on the docking probe.
Figure 11. Control Response during Translation - Roll Angle

Roll Angle

Time (seconds)

X command

Y command

Z command

Time (seconds)
Figure 13. Control Response during Translation - Pitch Angle
Figure 13 shows the results for MPOD's pitch angle during the same test. The pitch angle reference was set at 174 degrees. The actual angle was held within ±3 degrees of this reference. Because the test was run in a straight and level attitude, angle information from the yaw pendulum was highly inaccurate and is not presented here.

Figure 14. Control System response to Step Inputs - Pitch Angle

Figure 15. Control System response to Step Inputs - Roll Angle
Figures 14 and 15 show the closed loop response of the vehicle's pitch and roll angles during step changes in the reference pitch angle. After stabilizing the vehicle with a pitch angle of 170 degrees, and a roll angle of 176 degrees, the test began. At eight seconds, a thirty degree increment to the reference pitch angle was commanded. Seven seconds later, the vehicle's pitch angle stabilized within a few degrees of the new 200 degree reference. At forty seconds, the 200 degree reference angle was decremented by thirty degrees. Twelve seconds later, the pitch angle was reestablished within a few degrees of the original 170 degree reference. The higher overshoot and resulting increase in settling time observed in the case where the pitch angle was decremented, are believed to be due to an offset between the center of gravity and the center of buoyancy which augmented the control moment in that direction. Throughout the test, the vehicle remained within three or four degrees of the original reference roll angle.

The results shown above indicated the control system was acceptable for use in performance of the docking task. The controller performed exceptionally well in controlling MPOD's pitch angle. Control of the vehicle's roll angle was also good, despite the difficulties inherent in balancing MPOD around the roll axis and a hardware problem which caused one of the bottom y motors to operate erratically. Finally, though no data were taken which could quantify the control system's operation around the vertical axis, it was generally accepted that control would be poor due to the lack of proportional and integral feedback information from the pendulum rotating about that axis, and due to the severe degradation of the gyros supplying derivative feedback information to the controller. During testing, the vehicle did demonstrate a pronounced tendency to yaw about the vertical axis, and an attempt was made to upgrade the gyro package as a result. Unfortunately, the waiting period for the new rate sensors was 27 weeks. Although the drift of the vehicle about the yaw axis resulted in a slight increase in pilot workload, the final decision was to perform these experiments with the existing gyro package while the new sensors were on order.
Test Procedure

Graphics Display Orientation and Training

The selected mapping of vehicle movement to graphic movement was counterintuitive to many. Although it reinforced the video feedback, rather than conflicting with it (i.e. the rectangle became larger as the docking target was seen to get larger) a number of people were disturbed because the red markers moved in exactly the opposite direction of what was expected for a given hand controller input. In an attempt to familiarize the four test subjects with this pattern, each was asked to practice with a simulator before actual testing began.

The simulator displayed the same graphics seen during actual testing, overlaid on a plain white background. A random initial position and orientation for the vehicle was generated and the corresponding graphic symbology was displayed. The subject then moved the hand controllers such that the red graphics became coincident with the black reference frame. Each practice session consisted of ten of these runs.

Docking Task Setup

Neutral buoyancy testing of the complete system was performed in the MIT Alumni Swimming Pool in Cambridge, Massachusetts. In the docking task, the objective was to pilot MPOD on a nominal trajectory through the approach and engagement of a docking target located approximately six meters away. At the beginning of each run, either stereovision or monovision, and either use or non-use of the graphics overlay was selected. Scuba divers then positioned the vehicle at the starting point in a straight and level attitude. At this point, control was passed to the pilot, who engaged power, turned on the closed loop control system, and began the run. Figure 16 shows the basic arrangement of the underwater equipment. Note that the fourth 3DAPS hydrophone which extends out the left side of the vehicle can not be seen in the drawing.
Four test subjects were chosen to pilot the vehicle during these tests. Subjects were chosen on the basis of experience and demonstrated aptitude. Subject #1 had extensive experience piloting all three of the teleoperators in the SSL, and had piloted MPOD both remotely, and onboard. Subject #2 had significant experience as well, but had flown only MPOD, and only from a remote control station. Subject #3 had flown only a few familiarization runs with MPOD, but had substantial experience operating the Beam Assembly Teleoperator with the dual monitor stereovision system. Finally, subject #4 had minimal experience piloting two of the teleoperators, including piloting MPOD from remote, but had some related robotics experience and demonstrated exceptional proficiency for his level of training.

Figure 16. Underwater equipment arrangement
Each test run was timed with both a stopwatch, and with markers in the data file on the IBM AT computer. Timing began as the vehicle center crossed the third lane marker of the swimming pool. The vehicle was considered successfully docked once the pilot had inserted the docking probe into the drogue of the docking target and activated the ram, latching the vehicle to the target. Occasionally, a pilot would activate the ram before the vehicle was adequately positioned for the latches to catch the target. In this case, the pilot had to retract the ram, cycle the latches if necessary, and try to better position the vehicle before trying again. Timing of the task continued until a successful docking attempt was completed. When the task was finished, the pilot undocked from the target by withdrawing the ram, and deactivating the latches, releasing the target.

Experimental Results of Docking Task Testing

For the stereovision case, all four test subjects had shorter average docking times when the graphics overlay was used. In the monovision case, three of the four test subjects showed shorter average docking times when the overlay was present. What is interesting is that, in discussing strategy with the test subjects afterward, each claimed to have disregarded the graphics display almost entirely. They felt that the graphics display was not accurate enough nor was it updated frequently enough to supersede, or even to augment the real-time video signal from the vehicle. One explanation for the exhibited improvement was suggested by subject #1. He believed that the active graphics displayed in red were not as helpful as simply having the clear, static, black reference frame by which to judge the position of the vehicle relative to the target. Though the camera view included the docking probe mounted on the front of the vehicle, and consequently should have included virtually the same information concerning the relative positions of the vehicle and target as the overlaid reference frame, the clear, concise reference provided by the graphics display seemed to be easier to interpret and use.
Figure 17 gives a graphical display of the average docking times in each of the four test cases, for each test subject and over all tests performed. Table 1 lists the average, the maximum, and the minimum docking times, the number of tasks performed, and the standard deviation of the data, for each test subject, under each test condition. The last section of the table summarizes this information over all tests performed.

From this data, a comparison was also made between operation with stereovision and operation with conventional monovision feedback. It is interesting to note that the two trained test subjects showed little difference in the average time required to dock between cases where stereovision was employed, and those cases where it was not. It is believed that the trained test subjects had learned to compensate for the lack of depth cues in the monovision display. As a result, the depth information from the stereovision system used in these tests had little effect on
their average docking times. It is possible that, had the interocular distance between the stereo cameras been increased, the resulting hyperstereoptic view may have made a difference in these cases[9].

The untrained test subjects, however, showed marked differences between stereovision runs and monovision runs. Unfortunately, their data neither confirmed nor refuted the idea that stereovision feedback could be used to improve performance in such tasks. Results for subject #3 appeared to reflect his dislike of the stereovision system in general. Several factors contributed to this. First, there was detectable flicker in the picture generated by the stereovision system which resulted from alternating views for the right and left eyes. Most people simply ignored this, however subject #3 was accustomed to using the previous stereovision system which did not have this problem. It is believed that as a result, he found the flicker both distracting and disturbing.

Also, though it was not known at the time, the grounded shield on the video signal from the right camera was slowly deteriorating due to corrosion by chlorinated water which had leaked inside the outer casing of the umbilical cable to that camera. This resulted in a gradual degradation of the picture quality from that camera. This was not a significant effect when the camera was used alone to produce monovision feedback. However, it may have adversely affected the operator's perception of the stereovision image when the inferior signal from the right camera was interlaced with the unimpaired signal from the left camera.

In comparison, the results for subject #4 favored the use of stereovision. Unfortunately, the limited number of test runs performed by this subject prevents his data from being conclusive. It is worth noting that testing on this subject was performed early in the testing period, before the corrosion of the shield on the right camera video signal became a problem. This seems to indicated that the quality of the video feedback signal was important
for this stereovision system, and that even stereovision with the limited interocular distance used here may be helpful to untrained operators.

<table>
<thead>
<tr>
<th></th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subject #1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (min.)</td>
<td>1.94</td>
<td>1.11</td>
<td>1.95</td>
<td>1.62</td>
</tr>
<tr>
<td># of Runs</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.22</td>
<td>1.60</td>
<td>3.92</td>
<td>3.48</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.47</td>
<td>0.60</td>
<td>0.78</td>
<td>0.47</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>1.57</td>
<td>0.42</td>
<td>1.40</td>
<td>1.26</td>
</tr>
<tr>
<td><strong>Subject #2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (min.)</td>
<td>1.10</td>
<td>0.79</td>
<td>1.01</td>
<td>0.76</td>
</tr>
<tr>
<td># of Runs</td>
<td>14</td>
<td>15</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.66</td>
<td>1.55</td>
<td>2.57</td>
<td>2.15</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.42</td>
<td>0.45</td>
<td>0.37</td>
<td>0.40</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.72</td>
<td>0.37</td>
<td>0.69</td>
<td>0.47</td>
</tr>
<tr>
<td><strong>Subject #3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (min.)</td>
<td>1.17</td>
<td>2.00</td>
<td>3.55</td>
<td>3.28</td>
</tr>
<tr>
<td># of Runs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.00</td>
<td>3.75</td>
<td>7.38</td>
<td>7.55</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.63</td>
<td>0.75</td>
<td>1.17</td>
<td>0.97</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.64</td>
<td>1.37</td>
<td>2.74</td>
<td>2.92</td>
</tr>
<tr>
<td><strong>Subject #4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (min.)</td>
<td>3.24</td>
<td>2.43</td>
<td>1.93</td>
<td>1.39</td>
</tr>
<tr>
<td># of Runs</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.00</td>
<td>3.33</td>
<td>1.93</td>
<td>1.65</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.48</td>
<td>1.53</td>
<td>1.93</td>
<td>1.13</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>2.48</td>
<td>1.27</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td><strong>All Runs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (min.)</td>
<td>1.86</td>
<td>1.58</td>
<td>2.11</td>
<td>1.76</td>
</tr>
<tr>
<td># of Runs</td>
<td>25</td>
<td>26</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.00</td>
<td>3.75</td>
<td>7.38</td>
<td>7.55</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.42</td>
<td>0.45</td>
<td>0.37</td>
<td>0.40</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>1.18</td>
<td>0.85</td>
<td>1.58</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 1. Docking Times Summary

A second analysis of the docking tasks performed was done using stored data from the 3DAPS system. Both the calculated ranges from each emitter to each hydrophone, and the calculated hydrophone positions which resulted from that data, were stored during each test run. Later, the hydrophone positions were used to calculate the vehicle's position for each data point. Nominally, the vehicle's position simply would have translated along a line extending
back from the center of the target parallel to the 3DAPS y-axis. By calculating the distance of the vehicle center from this nominal trajectory, and averaging the results for each data point, an average trajectory error in meters was determined for each run. Table 2 summarizes the results of these calculations for each test subject and for all data runs, in each test configuration, including the average, maximum, and minimum trajectory error, the number of runs, and the standard deviation of the data.

<table>
<thead>
<tr>
<th>Subject #1</th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Error (m)</td>
<td>1.89</td>
<td>1.10</td>
<td>1.91</td>
<td>1.33</td>
</tr>
<tr>
<td># of RUNS</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.61</td>
<td>1.88</td>
<td>3.19</td>
<td>2.17</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.70</td>
<td>0.56</td>
<td>0.62</td>
<td>0.78</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>1.53</td>
<td>0.48</td>
<td>1.43</td>
<td>0.53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject #2</th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Error (m)</td>
<td>1.56</td>
<td>1.71</td>
<td>1.52</td>
<td>1.66</td>
</tr>
<tr>
<td># of RUNS</td>
<td>14</td>
<td>15</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.63</td>
<td>2.52</td>
<td>2.57</td>
<td>3.41</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.89</td>
<td>1.11</td>
<td>0.56</td>
<td>0.71</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.42</td>
<td>0.45</td>
<td>0.60</td>
<td>0.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject #3</th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Error (m)</td>
<td>0.96</td>
<td>1.17</td>
<td>0.90</td>
<td>1.09</td>
</tr>
<tr>
<td># of RUNS</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.37</td>
<td>1.47</td>
<td>1.18</td>
<td>1.50</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.42</td>
<td>0.91</td>
<td>0.58</td>
<td>0.60</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.45</td>
<td>0.24</td>
<td>0.27</td>
<td>0.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject #4</th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Error (m)</td>
<td>1.09</td>
<td>1.17</td>
<td>1.48</td>
<td>1.32</td>
</tr>
<tr>
<td># of RUNS</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.17</td>
<td>1.41</td>
<td>1.48</td>
<td>1.59</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.00</td>
<td>0.93</td>
<td>1.48</td>
<td>1.06</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.13</td>
<td>0.35</td>
<td>0.35</td>
<td>0.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>All Test Runs</th>
<th>Monovision</th>
<th>Mono. w/ Graph</th>
<th>Stereo</th>
<th>Stereo w/ Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Error (m)</td>
<td>1.37</td>
<td>1.29</td>
<td>1.45</td>
<td>1.35</td>
</tr>
<tr>
<td># of RUNS</td>
<td>25</td>
<td>26</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.61</td>
<td>2.52</td>
<td>3.19</td>
<td>3.41</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.42</td>
<td>0.56</td>
<td>0.56</td>
<td>0.60</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.84</td>
<td>0.50</td>
<td>0.80</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Table 2. Average Position Error Summary
Ideally, the data from all four of the 3DAPS hydrophones would have been used in order to reduce errors in the calculation of the vehicle's position and attitude. When data from all four hydrophones was available, they were taken in four groups of three, each group producing a separate estimate of the vehicle's position. The coordinates of these four points were then averaged to produce the most reliable estimate of vehicle position. Averaging the coordinates minimized the square of the error between the calculated points and this estimate.

Unfortunately, in approximately 85% of the tests conducted for this research, one of the four hydrophones failed to operate properly. These failures were most likely caused by a loose connection in the 3DAPS system, possibly in the receiver onboard MPOD. Four of the failures involved malfunction of the fourth hydrophone on the left side of the vehicle. The remaining 79 failures involved the third hydrophone attached at the back of the vehicle. Knowing this to be the case, the trajectory error calculations for those tests in which there was a failure were done using only the data from the three remaining hydrophones. This resulted in a slightly higher average trajectory error for those runs. In comparison with the average trajectory error calculated for tests in which all four hydrophones functioned properly, the average trajectory error calculated was an average of 4.6 times higher for tests in which the fourth hydrophone failed, and twice as high for cases in which the third hydrophone failed.

This fact was only significant in the results for subject #1. For the other subjects, an approximately equal number of failures occurred for each of the four test cases, and all of those failures involved the third hydrophone. For subject #1, however, two of the monovision-only tests, and two of the stereovision-only tests were done while the fourth hydrophone was malfunctioning. This lead to a considerable increase in the average trajectory error calculated for subject #1 under those conditions. This increase is clearly depicted in figure 18.
At each data point, the distance from the vehicle's center to the optimal trajectory line extending straight back from the target was calculated. In examining the average trajectory error with consideration for these failures, none of the subjects' results show a significant difference between any of the four cases. Generally less than two tenths of a meter difference can be seen between tests conducted with the graphics overlay and those conducted without it. The difference between tests employing the stereovision system and tests using only monovision was even less. Since this small an error in the position of the center of the vehicle was acceptable, even for actual docking of the docking probe with the target, it was not considered meaningful.

While the loss of a 3DAPS hydrophone had an adverse effect on the trajectory analysis, it had no effect on the generation of the graphics display. The calculations for the graphics did
not use the third hydrophone, and the fourth hydrophone failed only on runs in which the graphics display was not being generated.

**Conclusions and Recommendations**

The presence of a graphics display overlaid on the video signal transmitted from a telerobotic vehicle decreased the amount of time required to dock that vehicle by an average of 15% in monoscopic video cases, and 19% in stereoscopic video cases. It was unclear how much of this improvement was attributed to the active markers in the display which contained position and attitude information, and how much was a result of having a clear reference (i.e. the black reference graphics) by which the vehicles position and attitude with respect to the target could be judged. It is possible that both were responsible to some degree. Future experiments of this type should include tests in which the reference is displayed, but the position and attitude markers are not, and perhaps also tests in which the position and attitude markers are displayed without the reference. These experiments would help determine to what extent the reference frame alone assisted in the task.

For future experiments, several improvements could be made to the control system used on MPOD. First, a pressure sensor used to determine the approximate depth of the vehicle has been successfully integrated into the control system, allowing limited control of the vehicle’s depth as well as attitude. The incorporation of new rate sensors currently on order should allow much better control about the vertical axis. Also, though it was possible to alter each of the control gains for each of the vehicle axes independently, initially there seemed to be no clear advantage to doing this. It is possible that increasing the derivative gain about the vehicle’s z-axis would have improved performance of the controller about the vertical axis, which for these experiments was almost always the z-axis. This is almost certainly true for the new sensors, but may not be true given the extreme degradation of the output signal from the existing sensors.
Several improvements could also be made involving the 3DAPS system. It is believed that the excessively slow update rate of the translational position and unreliable angle information obtained from the 3DAPS system limited the amount of improvement in operator performance resulting from the display of active position and attitude markers. It is conceivable that the 3DAPS system could be redesigned so that emitters, each of which has a unique frequency, fire simultaneously. By parallel processing the emitter signals from such a system, the update rate would be increased considerably. Updating the graphics symbols for all six degrees-of-freedom more frequently would reduce the need for the operator to extrapolate his current position and attitude from the last display.

Limited accuracy in the information from the 3DAPS system may have also restricted the degree of improvement resulting from the display. Two factors contributed to this. First, 3DAPS seems to be more accurate for slow moving objects and MPOD can travel at a relatively high rate of speed under full thrust. Second, accuracy of the information was further reduced by the loss of data from one of the hydrophones in a significant number of the tests run. The same processing scheme suggested above to increase the update rate could also improve results for faster moving objects. The new system should be made more robust, however, in order to avoid problems such as those stemming from the loss of data from a hydrophone.

Given that a significant improvement in performance was indicated despite the limitations of the 3DAPS system, an even higher level of performance may be achieved if the update rate can be increased, the level of accuracy elevated, and the system as a whole made more robust.

Another problem encountered during testing of the complete system was failure of the fiber optics communications links. Use of fiber optics reduced weight and drag on the vehicle related to the communications link and allowed faulty cables to be replaced without removing the vehicle from the water. However, many of the components in the fiber optic system were
relatively fragile. Some of the problems experienced included broken connectors, slippage of the end-connectors off the optic fiber, pinching of the cable which caused degradation of the signal, and failure of the receivers and transmitters which converted the signal at the ends of the cables.

Improvements might also be made in the stereovision system. If a practical way could be found to increase the frame rate of the display, the flicker would be reduced. Also, video amplifiers on the signals going into the stereo electronics system from the right and left cameras would help counter the problem of attenuation by the umbilical link and the video card in the Macintosh II used to overlay the graphics.

As a final note, while the neutral buoyancy method of space simulation is more accessible, less costly, and less constrained than both other methods of simulation and actual experimentation in space, it does require a significant amount of time, effort, and expense. As in other methods of space simulation, it can be very difficult to obtain statistically significant results because the number of data runs which can be accomplished is limited by the amount of time available for testing in the simulation facility. Performing a large, equal number of tests on a sizable number of equally trained subjects can be virtually impossible. This means that the data presented here should be considered indicative rather than conclusive. Still, several interesting observations were made: 1) a graphic display representing vehicle position and attitude, overlaid on the video image transmitted from that vehicle, reduced the average time required to perform a teleoperated docking task in both monoscopic and stereoscopic modes of operation, 2) use of stereovision to improve depth perception had little effect on test subjects familiar with the task, and 3) data from tests performed by untrained subjects using the stereovision system indicated that the added depth perception might be beneficial for inexperienced subjects, but that factors such as quality of the stereo image and previous experience played an important role.
References:


Appendix A: Closed Loop Control System Information

The closed loop equation of motion for the simplified MPOD model (i.e. simple integrator) is:

\[ \ddot{\Theta} = -K_P \Delta \Theta - K_I \dot{\Theta} - K_D \dot{\Theta} \]

First, an initial estimate for \( K_P \) and \( K_D \) was determined. Given a proposed worst case situation where, around a given axis, the angular position error is .25 radians and the vehicle is rotating at a rate of .25 radians per second, the proportional, integral and derivative gains necessary to produce maximum thrust output from the ducted propellers may be calculated. Momentarily disregarding the integral term, the above equation becomes:

\[ \ddot{\Theta} = -0.25K_P - 0.25K_D \]

and for unit torque, \(|K_P| + |K_D| \approx 4\). Choosing \( K_P = K_D = 2 \) gives the following:

\[ \ddot{\Theta} + 2 \dot{\Theta} + 2 \Delta \Theta = 0 \]

This yields a quick, well-damped transient response with \( \xi = \sqrt{2}/2 \), and \( \omega_n = \sqrt{2} \) rad/sec.

Next, these values for \( K_P \) and \( K_D \) were converted into the appropriate units for the onboard computer calculations. This conversion was necessary for two reasons. First, the pendula were read using optical encoders and circuitry which produced 4,096 digital counts per revolution, and the outputs from the rate gyros were specified at 128 A/D counts (2.5 volts) for a maximum rotation rate of 180°/second. Second, the values were calculated to produce a single unit of thrust, so they had to be scaled to produce the maximum output. Since MPOD's software was designed to respond to a digital hand controller input which ranged from 0, for full negative deflection, to 255 for full positive deflection, these "hand controller units" were used in place of actual thrust or torque units. More specifically, full thruster output of 178
N/thruster pair was mapped to full hand controller deflection of 128 counts. This resulted in the following preliminary gain values:

\[ K_p = 2 \times \frac{3.14 \text{ rad}}{4096 \text{ counts}} \times 128 \text{ hand controller units} \]

\[ = 0.19625 \]

\[ = 2^{-2} \]

\[ K_D = 2 \times \frac{1.57 \text{ rad/sec}}{128 \text{ counts}} \times 128 \text{ hand controller units} \]

\[ = 3.14 \]

\[ = 2^2 \]

During the control system evaluation tests, a more accurate value was experimentally determined for the sensitivity of the gyro. Using that information, it was determined that the original estimate for the derivative gain should be doubled. Details of that recalculation are shown below.

\[ K_D = 2 \times \frac{3.584 \text{ rad/sec}}{128 \text{ counts}} \times 128 \text{ hand controller units} \]

\[ = 7.168 \]

\[ = 2^3 \]

Using a method similar to the one used to determine the proportional and derivative gains, an estimate was made for the integral term. This was done by calculating the integral gain required to produce full corrective thrust in a hypothetical worst case where a .25 radian error has existed for one second. To produce the integral term for a particular axis, a number which is the sum of the differences between the reference encoder readings and the current encoder reading for that axis, was multiplied by the integral gain. A .25 radian error resulted in an error of approximately 163 encoder counts each control cycle. Given a cycle time for the control loop of approximately one seventh of a second, the sum of these errors over a second...
was 1,141. The integral gain effectively scaled this number to produce the equivalent of a fully deflected hand controller reading. Dividing by 128 gives the proper scaling factor, and approximate integral gain as 0.1123, or approximately 2⁻³.

Even though the onboard software for MPOD was programmed in the "C" programming language, an attempt was made to make any numerical calculations in the control loop as efficient as possible to reduce the cycle time of the control loop. This was especially important because calculation of the integral term of the controller assumed this control cycle time was short enough to justify simple summing of the error to produce the integral term. Rounding the values calculated for the control gains to the nearest power of two allowed right or left bit shifting to be used in place of multiplication and division.

The proportional and derivative parts of the controller worked well under virtually all conditions; in experimentation, however, the addition of integral feedback frequently caused the system to go unstable. In the final control system implementation, use of a relatively small integral gain and limitation of the magnitude of the integral term itself prevented such instabilities.

To determine the best gain settings, the vehicle was operated in closed loop mode while the gain values were set to the calculated estimates and then adjusted by factors of two both above and below those gain settings. Many of these configurations were either clearly unstable, or inadequate for use in the docking task. Of the combinations considered acceptable, setting \( K_P = 2^0 \), \( K_I = 2⁻^5 \), and \( K_D = 2^4 \) resulted in the best response to operation during commanded translations and commanded step inputs in pitch angle. The subroutine used to calculate the proportional, integral, and derivative terms as a function of the onboard sensor readings is listed below.
This is an algorithm for calculating closed loop control values for onboard control of MPOD. This routine produces effective rotational hand controller inputs which can be passed directly to a jet select routine. The outputs range from 0x00 (full negative) to 0xFF (full positive).

NOTE: Commands from the operator via the rotational hand controller take precedence over commands from the control system. The control, or reference angles for the control system are set to the current vehicle angles when the system is initially engaged. They are reset by using the rotational hand controller to establish the desired attitude. Releasing the rotational hand controller sets the reference angles to the newly established vehicle angles.

Program started 1/22/89 by Vicky Rowley

Further modified, PiVeCS integration,
1/27/89 15:00 by RMS
1/29/89 13:30
1/30/89 12:10
1/31/89 10:26
3/04/89 14:50
Program last modified 4/16/89

void CL_Calc(CntlChg, Torque)
unsigned char CntlChg, *Torque;
{
    static unsigned char ang_rely[3]; /* Reliable axis flags */
    static long Error[3];
    static unsigned long I_Term[3];

    int delrhc;
    long Temp;
    unsigned long utemp, E_Temp;
    register i, j;

    if (CntlChg) {
        for (i = 0; i < 3; i++) {
            refang[i] = Pendula[i];
            I_Term[i] = Error[i] = 0;
        }
    }

    if ( ((Pendula[0]>=35841||Pendula[0]<=512)     
        || ((Pendula[0]>=1536&&Pendula[0]<=2560)    
    else
        ang_rely[2] = TRUE;
if ( ((Pendula[0]>2560&&Pendula[0]<3584)  
        &&(Pendula[0]>512&&Pendula[0]<1536)) )  
    ang_rely[1] = FALSE;
else
    ang_rely[1] = TRUE;

    ang_rely[0] = FALSE;
else
    ang_rely[0] = TRUE;

/* Compute torques about all three axes */
for (i = 0; i < 3; i++) {  
    if (rhc[i] > 0x7A && rhc[i] < 0x85) {  
        Torque[i] = 0x80;
        Temp = 0x80;
    }  
    else {  
        if (POSILIM - Error[i] > E_Temp)  
            Error[i] += POSILIM - E_Temp;
        else  
            Error[i] = POSILIM;
    }  
}  
else {  
    if (POSILIM - Error[i] > E_Temp)  
        Error[i] += 4096 - E_Temp;
    else  
        Error[i] = POSILIM;
    if (PID & P_CNTL){  
        utemp = E_Temp >> 2;
        utemp <<= Gains[0][i];
        Temp += utemp;
    }  
}  
else {  
    if ( (E_Temp = refang[i]-Pendula[i]) < 2048) {  
        if (POSILIM - Error[i] > E_Temp)  
            Error[i] += POSILIM - E_Temp;
        else  
            Error[i] = POSILIM;
    }  
}
Error[i] = POSILIM;
if (PID & P_CNTL){
    utemp = E_Temp >> 2;
    utemp <<= Gains[0][i];
    Temp += utemp;
}
else {
    if ( Error[i] - NEGILIM > E_Temp )
        Error[i] += E_Temp - 4096;
    else
        Error[i] = NEGILIM;
    if (PID & P_CNTL){
        utemp = (4096 - E_Temp) >> 2;
        utemp <<= Gains[0][i];
        Temp -= utemp;
    }
} /* End unsigned checking and bit shifting of encoders */

/* Compute the running integral term */
if (Error[i] < 0)
    I_Term[i] = (unsigned long) (-Error[i]);
else
    I_Term[i] = (unsigned long) Error[i];

/* Begin computation of I control torques */
if (PID & I_CNTL) {
    if (Error[i]<0)
        Temp -= ((I_Term[i] >> 4) >> Gains[1][i]);
    else
        Temp += ((I_Term[i] >> 4) >> Gains[1][i]);
} /* End computation of I control torques */

} /* End reliable axis decision block */

/* Compute D control torques regardless for all axes */
if (PID & D_CNTL) {
    if (Gyros[i] >= 0x7B)
        Temp -= (Gyros[i] - 0x79) << (Gains[2][i]+2);
    else if (Gyros[i] <= 0x77)
        Temp += (0x79 - Gyros[i]) << (Gains[2][i]+2);
} /* End computation of D control torques */

} /* End loop for case of no hand controller input */

/* If there's a significant rhc input, set Temp = rhc[i].*/
else{
    refang[i] = Pendula[i];
    Temp = rhc[i];
    if (Error[i]<0)
        Temp -= ((I_Term[i] >> 4) >> Gains[1][i]);
    else
        Temp += ((I_Term[i] >> 4) >> Gains[1][i]);
} /* End CL_Calc */

} /* End torque computation block */

if (Temp > 0xFF)     Torque[i] = 0xFF;
else if (Temp < 0x00) Torque[i] = 0x00;
else                Torque[i] = (unsigned short)Temp;

} /* Make sure the output torque commands are 0x00–0xFF */
Appendix B: Algorithms for determination of vehicle position and attitude used in trajectory analysis and graphics display generation

The matrix transformation method used to calculate estimates for the position of the vehicle's center was relatively straightforward. At each data point of a test, a 4x4 matrix representing the transformation matrix between the MPOD coordinate system and the 3DAPS coordinate system was calculated using the stored hydrophone positions obtained from 3DAPS during that test. The mathematics of this matrix, which relates the two coordinate frames both rotationally and translationally, may be found elsewhere[5].

This matrix was found by introducing a third intermediate coordinate system to which the relation of the MPOD and 3DAPS coordinate systems was known. The hydrophones themselves provided the basis for just such a system. Knowledge of the individual hydrophones' attachment points on MPOD made it possible to derive a single transformation matrix relating the positions of the hydrophones to the MPOD coordinate system. Using the data obtained during a test by the 3DAPS system, a similar matrix, relating the positions of the hydrophones to the 3DAPS coordinate system, was calculated for each data point. The matrix relating MPOD's position and attitude to the 3DAPS coordinate system was obtained by multiplying these matrices.

Ideally, each of the four possible sets of three hydrophones were used to establish the intermediate coordinate system, resulting in four matrices relating MPOD's position and attitude to the 3DAPS coordinate system, and producing four corresponding estimates for the position of the vehicle center. Averaging these four estimates minimized the sum of the square of the errors from each of the estimates to the average point. This average was used as the actual vehicle position in calculating the trajectory error of the vehicle for that point.

In cases where the position of one of the hydrophones was not updated properly by the 3DAPS system, only information on the three remaining hydrophones was used, and only one estimate for the position of the vehicle was acquired at each data point. This estimate was used
as the actual vehicle position in calculating the trajectory error of the vehicle at that point, with consequently larger trajectory errors resulting from the 25% reduction in available information.

Calculation of the vehicle trajectory error was done for each data point of a test run. These errors were averaged to produce a single number indicating how close the vehicle remained to the nominal trajectory during that run. Calculating the error for an individual point was as simple as calculating the distance from the vehicle center to the line of the nominal trajectory. This nominal trajectory was a straight line with the parametric form $x=4115$ (mm), $y=t$, $z=2083$ (mm).

Rather than using the time consuming matrix methods used to determine vehicle position for trajectory analysis, a simpler method was employed for graphics generation to insure that the graphics display would be updated during the time spent waiting for new 3DAPS information to become available. The position of the vehicle center was calculated by averaging the coordinates of the two hydrophones attached to the right and left sides of the vehicle. Only the vehicle's yaw angle was determined using information provided by the 3DAPS system. Information for the roll and pitch angles was provided by the pendula onboard MPOD.
Appendix C: Neutral Buoyancy Testing

All neutral buoyancy testing for the work presented here was performed in the MIT Alumni Swimming Pool. Preparing MPOD for the prolonged submergence involved in this type of testing required a number of provisions to be made. Before each test, any electronics or battery boxes opened since the last underwater operation had to be resealed and reinstalled in the vehicle. Typically both battery boxes and the control box required resealing. Next, necessary electrical power and signal connections were made using waterproof connectors, and any system requiring pressurization was connected to the onboard pressure system. Finally, all of the side foam panels, including the two x-thruster panels, were reattached to MPOD's aluminum frame. These panels were removed after each operation to facilitate servicing, maintenance and inspection of the vehicle's systems. At this point, the power relay, the thruster pairs, and the docking probe ram and latches elements were checked for proper operation before the vehicle was lowered into the water using an aluminum support structure which extended out over the water.

Once submerged, MPOD was under the supervision of two or three scuba divers who regularly monitored the various systems and umbilicals, and who performed tasks which required human intercession. In general, the first order of business for the divers was to properly balance the vehicle. This involved attaching small lead weights to the foam panels in appropriate places. The idea behind balancing the vehicle was to manipulate the center of gravity and the center of buoyancy so that they had as nearly the same position as was possible, while simultaneously equalizing the gravitational and buoyant forces on the vehicle. This minimized the torque on the vehicle resulting from any position offset not aligned with the gravity vector, and reduced any tendency of the vehicle to drift up or down.

Once the balance of the vehicle was adequate, there were still a few things which had to be done by the scuba divers before MPOD was ready to be flown. The toggle switches controlling power to the vehicle electronic systems had to be switched on, and the counters for
the pendulum encoders had to be indexed by rotating the vehicle around its individual axes. Also, if 3DAPS was to be used, the hydrophones had to be placed in their appropriate positions extending from the sides of the vehicle.

MPOD was now ready to be controlled from RECS. The power relay was activated by pressing a button on the rotational hand controller. This made power available to the thrusters, at which time MPOD could be flown in open-loop mode. A second hand controller button was used to toggle between open- and closed-loop operation. The third hand controller button was used to extend the docking probe ram into the drogue of the docking target. The trigger at the front of the rotational hand controller was used to toggle the latches.
Appendix D: Sample error and trajectory plots for each test case

Figures 19, 20, and 21 show plots of the data for an example run from each test case. All of the plotted runs were executed by the same test subject. Figure 19 shows plots of the vehicle position error as a function of time. Figures 20 and 21 show two-dimensional plots of the vehicle's trajectory. Figure 20 is a plot of the x-position against the y-position, or effectively the view from above the pool. Figure 21 is a plot of the z-position against the y-position, which is effectively a side view of the trajectory. The dashed line in the plots of figures 20 and 21 represents the nominal trajectory for the vehicle.

It can be seen in these plots, that the position error did not go to zero as the vehicle docked with the target. There are three explanations for this. The target was not rigidly fixed to the side of the pool, but hung from the side gutters. As MPOD docked with the target, the target was frequently moved to one side or the other by the vehicle. This is part of the reason for errors in the x-direction. Also, a certain amount of error in the positioning of the vehicle was allowed in successful docking. This was especially true for deviations of the vehicle's attitude from straight and level. Attitude errors of five or even ten degrees were acceptable for docking, but this caused the center of the vehicle to be off the line of the nominal trajectory by as much as 0.25 meters. Furthermore, when MPOD was docked with the target, it was near the wall. It is believed that this positioning exacerbated errors due to reflections and blockages of the hydrophones. This resulted in increased errors in the 3DAPS data as the vehicle drew near the target.
Figure 19. Sample Error Plots

Monovision

Monovision with graphics

Stereovision

Stereovision with graphics
Figure 20. Sample X-Y Trajectory Plots

Monovision only

Monovision with graphics

Stereovision only

Stereovision with graphics
Figure 21. Sample Y-Z Trajectory Plots

Monovision only

Monovision with graphics

Stereovision only

Stereovision with graphics