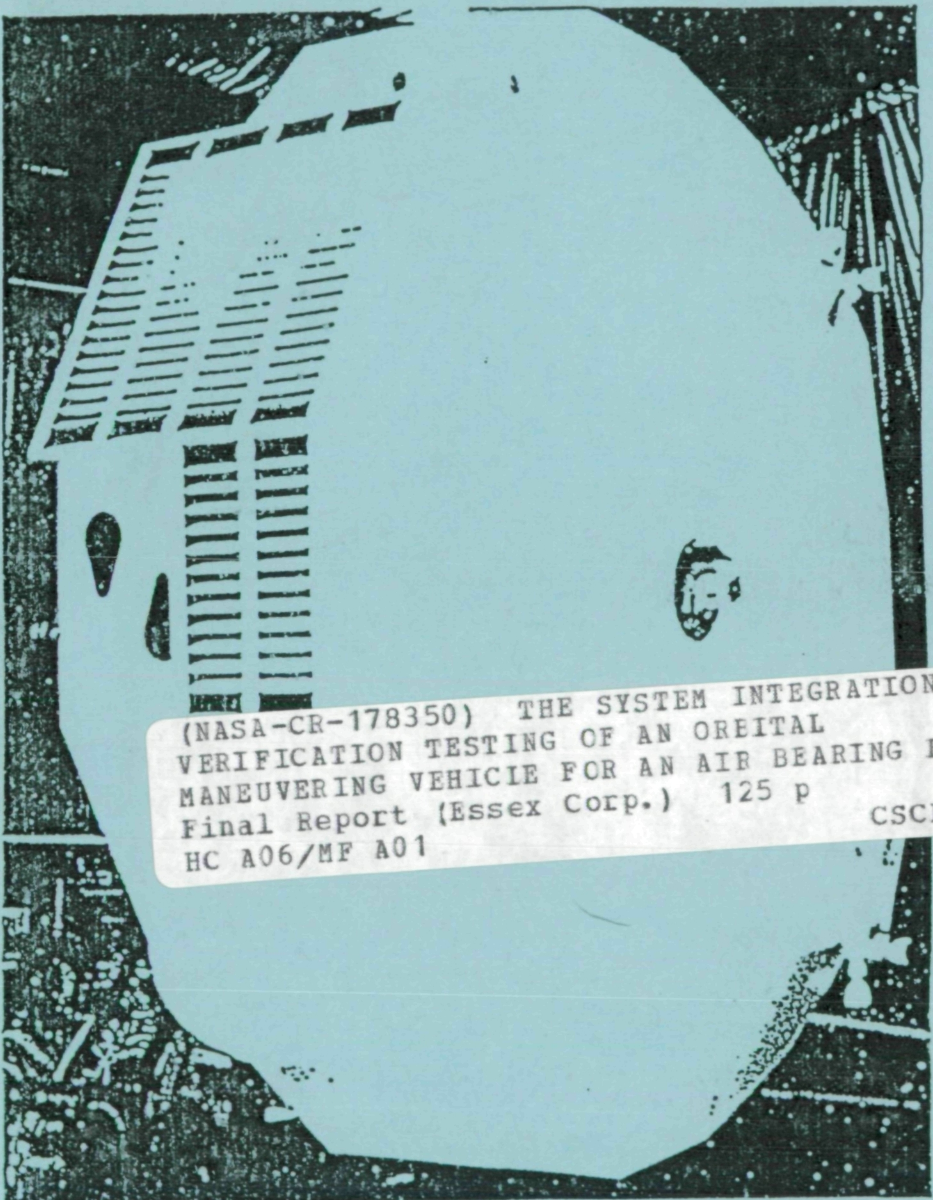
Fred Roe EB24

The System Integration and Verification Testing of an Orbital Maneuvering Vehicle for an Air Bearing Floor



Final Report

Contract NAS8-35636

February 22, 1986

ESSEX CORPORATION

SPACE SYSTEMS GROUP
690 Discovery Drive • Huntsville, Alabama 35806

THE SYSTEM INTEGRATION AND VERIFICATION TESTING

OF AN ORBITAL MANEUVERING VEHICLE

FOR AN AIR BEARING FLOOR

Contract NAS8-35636
Final Report
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PREPARED BY:

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PREPARED FOR:
Teleoperator and Robotics Evaluation Facility
Control Electronics Branch
George C. Marshall Space Flight Center
National Aeronautics and Space Administration

REPORT NO. H-86-02

FOREWORD

This contract final report marks the beginning of an opportunity to systematically explore human/system interactions and human authority over remote systems in a sophisticated simulation facility. The components of this simulation facility are the 4,000-square-foot precision air bearing floor, the Teleoperator Motion Base, the Target Motion and Support Simulator, the mock-ups of the Hubble Space Telescope, Multi-Mission Modular Spacecraft, and the Orbital Maneuvering Vehicle, the engineering control station, and the remote operator's Reconfigurable Workstation. The facility was designed and built to provide Marshall Space Flight Center (MSFC) with unequalled capability to support remote systems simulations. During the past two years, Essex Corporation technical staff members have integrated each of these elements with all the other elements of the laboratory and verified the operational capabilities of the laboratory through a series of tests. The result of all the design, fabrication, and technical effort is reflected in the Teleoperator and Robotics Evaluation Facility (TOREF) in Building 4619 of the Marshall Space Flight Center.

Such a facility would not be possible without the foresight and dedication of the engineering, technical, and management staff of MSFC and the innovative and diligent approaches taken by Essex staff members. The authors would like to recognize several Essex staff members who contributed to the success of the Teleoperator program: Crystal Sulyma, Tom Loughhead, Roger Winkler, and Doug Young. Among those NASA personnel who deserve recognition are E. C. Smith, Wayne Wagnon, Tom Bryan, and Frank Nola. The following MSFC employees served as subjects in the test series and their contributions are greatly appreciated: Elaine Hinman, Mike VanHooser, Michele Roeske, Steve Hall, John Ormsby, Bridgette McKinley, Bill Jacobs, and Jim Randolph. The assistance of Dr. Sue W. Kirkpatrick in the areas of test design and data analysis was a valuable asset. Finally, special appreciation is extended to Fred Roe, the TOREF facility manager and contract technical monitor for this effort. His sense of the TOREF's potential benefits and his recognition of the facility's widely varied applications kept the technical team

enthusiastic and pointed in the same direction for the past several years.

The contract final report has been organized to reflect the growing need for documentation as the contract requirements changed. The three textual parts of this document describe: (1) the Teleoperator and Robotics Evaluation Facility and its general capabilities to support Orbital Maneuvering Vehicle (OMV) and other remote system simulations; (2) the facility operating procedures and requirements; and (3) the results of generic OMV investigations.

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LIST OF ACRONYMS AND ABBREVIATIONS

C&DM - Communications and Data Management Subsystems
CID - Charged Induction Device
CRL - Central Research Laboratories
CRT - Cathode-Ray Tube
CTU - Command/Telemetry Unit
DOF - Degree-of-Freedom
DTS - Dynamic Target Simulator
FAA - Federal Aviation Administration
FCFS - Flight Configured Fresnel System
FOV - Field-of-View
fr/s - Frames Per Second
GCC - Ground Control Console
GE - General Electric
HST - Hubble Space Telescope
MMC - Martin Marietta Corporation
MMS - Multi-Mission Modular Spacecraft
MSFC - Marshall Space Flight Center
MTF - Modulation Transfer Function
NASA - National Aeronautics and Space Administration
NOSC - Naval Ocean Systems Center
OMV - Orbital Maneuvering Vehicle
PLZT - Piezioelectric Lathanum Lead Zirconate Titanate
RF - Radio Frequency
RMS - Remote Manipulator System
RPV - Remotely Piloted Vehicle
RWS - Reconfigurable Workstation
TMG - Target Motion Generator
TMS - Teleoperator Maneuvering System
TMSS - Target Motion and Support Simulator
TOM-B - Teleoperator Motion Base
TOREF - Teleoperator and Robotics Evaluation Facility
2-D - Two-Dimensional
3-D - Three-Dimensional

The System Integration and Verification Testing of an Orbital Maneuvering Vehicle for an Air Bearing Floor

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February 22, 1986

PART 1 FACILITY INTEGRATION

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1.0 INTRODUCTION

From 1971 through 1983, the subsystems necessary for remote operations were studied in isolated laboratories and evaluation facilities at the Marshall Space Flight Center. This served a two-fold purpose: investigators could study the primary contributions of the major subsystems -- displays, controls, mobility units, manipulators, lighting systems, etc. -- toward the human operator's ability to perform remote, or teleoperated, tasks, and the investigations could be carried out in small human performance laboratories with relatively simple equipment.

Studying the primary effects of major subsystems provided knowledge about the relative importance of, for example, various types of visual subsystems, without having the information influenced by other factors such as flight mobility subsystems or manipulator subsystems. Similarly, the mobility and manipulator subsystems could be studied without confounding the results with the influences of other subsystems. As a result of these investigations between 1972 and 1982, over 27 technical reports were published detailing the individual studies of the major subsystems.

Once the primary effects of the major subsystems were understood, incremental integration of the subsystems was undertaken. Video subsystems and manipulator subsystems were combined, as were manipulator subsystems and mobility subsystems, and so on. Eventually, it became necessary to integrate all the subsystems into one laboratory in order to perform system level simulations and evaluations. This section of Contract NAS8-35636 Final Report details the integration of the components of the Teleoperator and Robotics Evaluation Facility (TOREF) into NASA's largest and most versatile remote systems simulation facility. The facility is centered around a 44 by 88 foot precision air bearing floor, the largest of its kind. A mobility unit, isolated control room, and support equipment were integrated into the facility to provide the means for remote operation simulations. The facility layout and physical configuration are shown in Figure 1.1.

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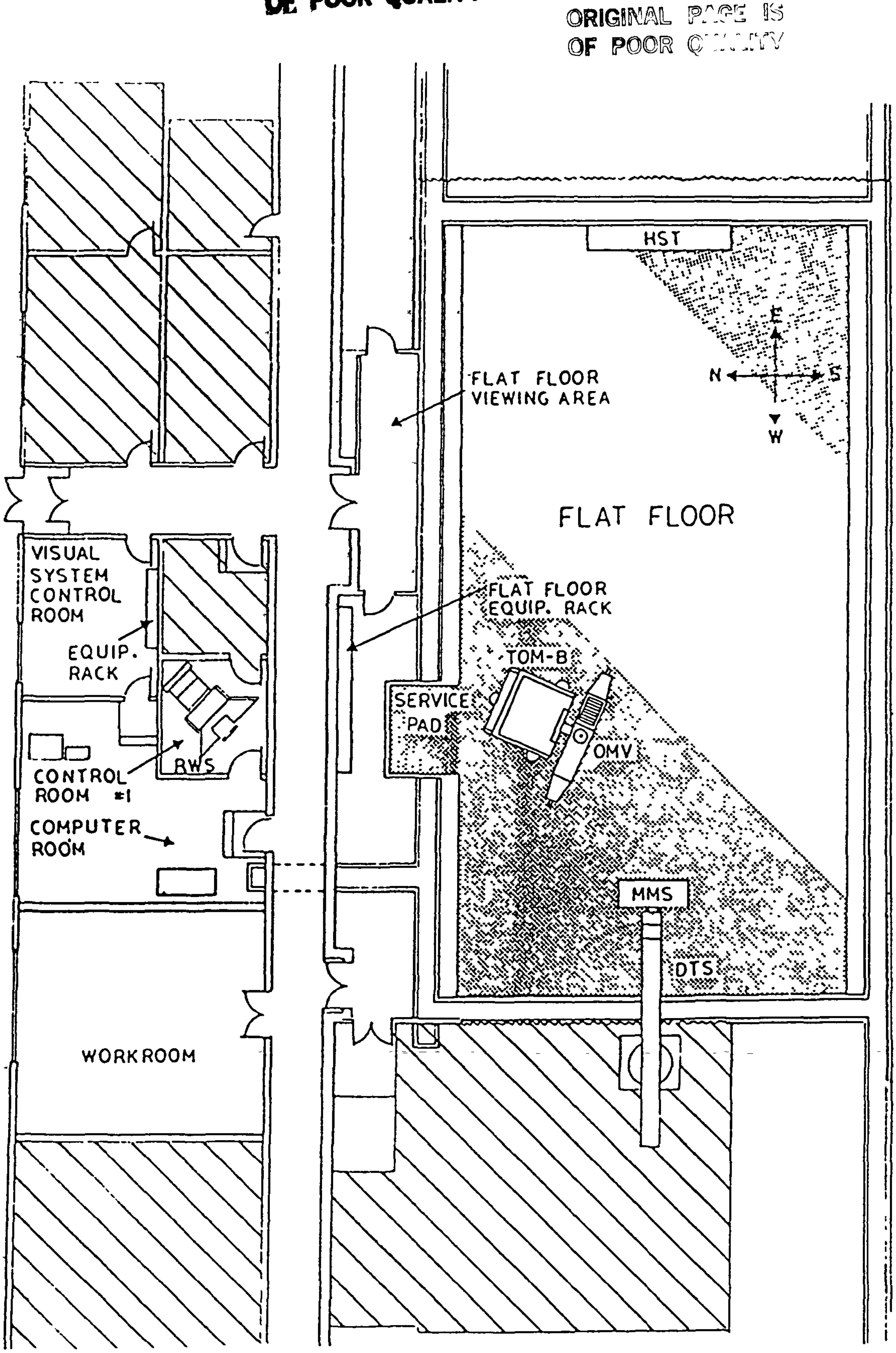

Figure 1.1: Teleoperator and Robotics Evaluation Facility (TOREF) Laboratory Layout

2.0 SYSTEMS LEVEL LABORATORY DESCRIPTION

Six main laboratory subsystems were necessary to perform the remote operation tasks required for teleoperator simulations. This section describes the mobility, control/command/telemetry, visual, target and docking, data collection, and communications systems which were incorporated into the laboratory. System documentation is provided by figures in the text and in an appended drawing package.

2.1 Mobility Systems

Central to the TOREF are three dynamic motion simulator systems. The Teleoperator Motion Base (TOM-B), the Target Motion and Support Simulator (TMSS), and the Dynamic Target Simulator (DTS) each provide the means for simulating spacecraft movement in up to six degrees-of-freedom (6DOF) toward fixed or dynamic targets. The TOM-B and TMSS move on precision air bearings over the flat floor, and the DTS is essentially a robot arm which is operated from the west end of the flat floor. Different levels of control are incorporated into each mobility system and each system is equipped with a standard mounting plate which is compatible with any of the TOREF mock-ups or targets.

<u>Teleoperator Motion Base (TOM-B)</u>

The TOM-B (Figure 1.2) is the most versatile and complex component in the TOREF. This 6DOF air bearing vehicle may serve as a maneuvering/docking craft or as a target craft. With self-contained electrical and pneumatic systems, the TOM-B is capable of completely remote operation from the control room.

The TOM-B system contains six 3,600 psi air tanks for pneumatic power, and the pneumatic system can be refilled at the flat floor service pad. The TOM-B electrical systems are powered by three separate wet-cell battery packs which can be recharged simultaneously at the service pad. Thirty-two, 2.8lb thrusters, located on eight plena around the perimeter of the motion base, provide X, Y, and yaw axes of motion. The remaining three axes of motion--pitch, roll, and Z--are provided by electric motors and drive trains. A detailed description of the TOM-B is provided in Teleoperator and Teleoperator Thruster Control, Contract No. NAS8-34726 Final Report No. H-85-04.

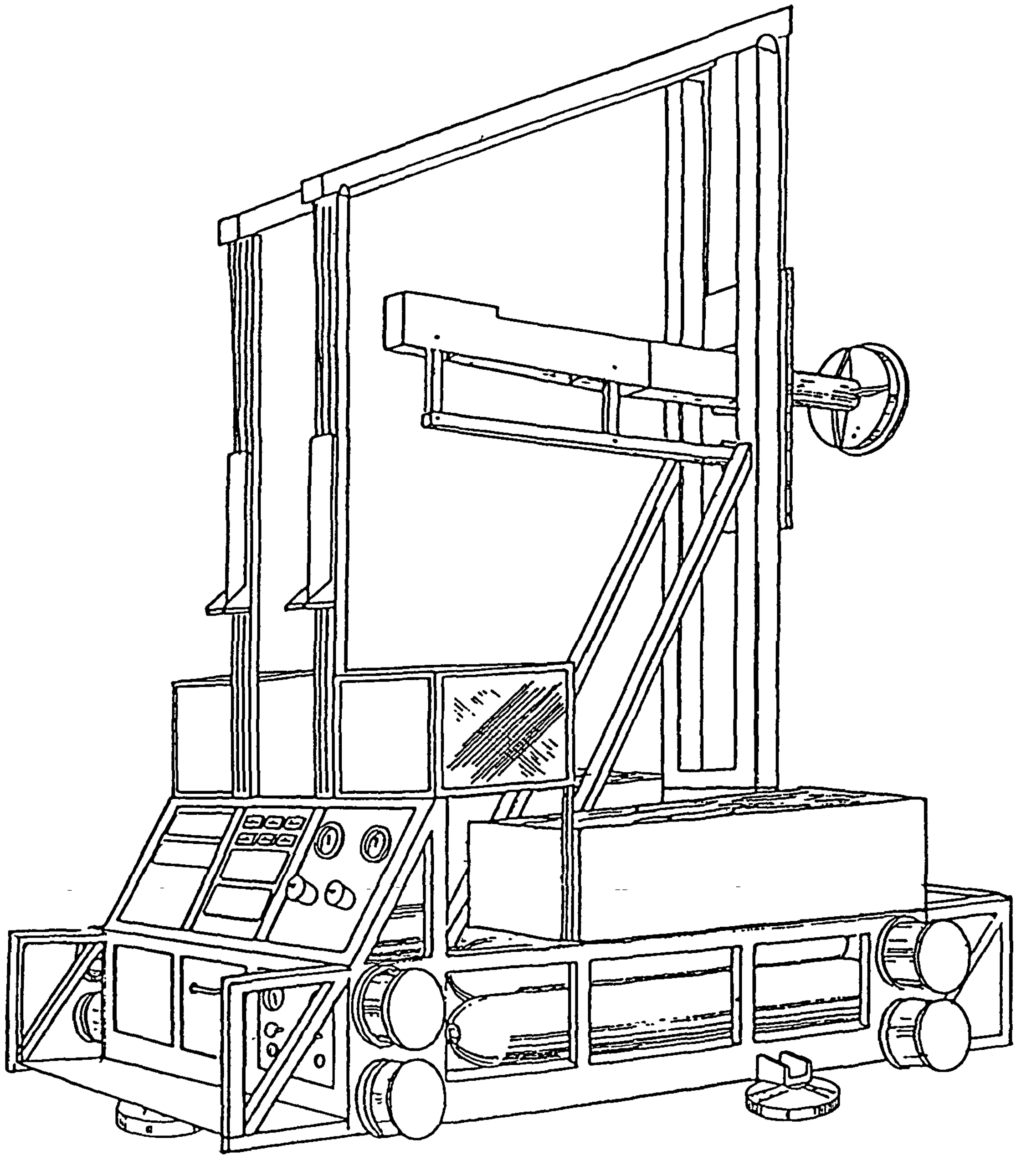

Figure 1.2: Teleoperator Motion Base (TOM-B)

Target Motion and Support Simulator (TMSS)

The TMSS is used on the flat floor to mount mock-ups and targets. Unlike the TOM-B, the TMSS is not a self-contained mobility unit. The TMSS pneumatic and electrical systems are powered through an external umbilical. The TMSS floats freely in the X, Y, and yaw axes on the flat floor and two motor drives provide Z and roll movements. The TMSS has a much smaller payload capability than the TOM-B. The TMSS has been described in Contract No. NAS8-34388 Final Documentation (1982).

Dynamic Target Simulator (DTS)

The DTS is a 6DOF robot arm with a 1,0001b payload capability and a 20ft reach over the flat floor. The DTS is mounted at the west end of the flat floor and can simulate realistic spacecraft motions. The DTS may be used as a target craft or docking/maneuvering craft with respect to the TOM-B. Documentation on the DTS is available from Marshall Space Flight Center, EB24.

2.2 Control/Command/Telemetry System

The Control/Command/Telemetry System provides the equipment necessary for controlling the remote operation of the TOM-B. This system is composed of a workstation, system controls, and a command/telemetry link.

The Reconfigurable Workstation (RWS)

The RWS was designed and built by Essex to meet the requirements of the TOREF for a general purpose, reconfigurable, remote systems workstation. The RWS, located in Control Room 1 (Figure 1.1), has been described in Analysis and Selection of a Remote Docking Simulation Visual Display System, Contract NAS8-35473 Final Report No. H-84-04. The RWS provides a primary worksurface which supports the operator's forearms during hand controller operation, a primary visual panel which holds two 33cm monitors, and a 91 x 123cm large screen display. The workstation also has panels for test-specific controls and displays. The RWS is shown in Figures 1.3 and 1.4.

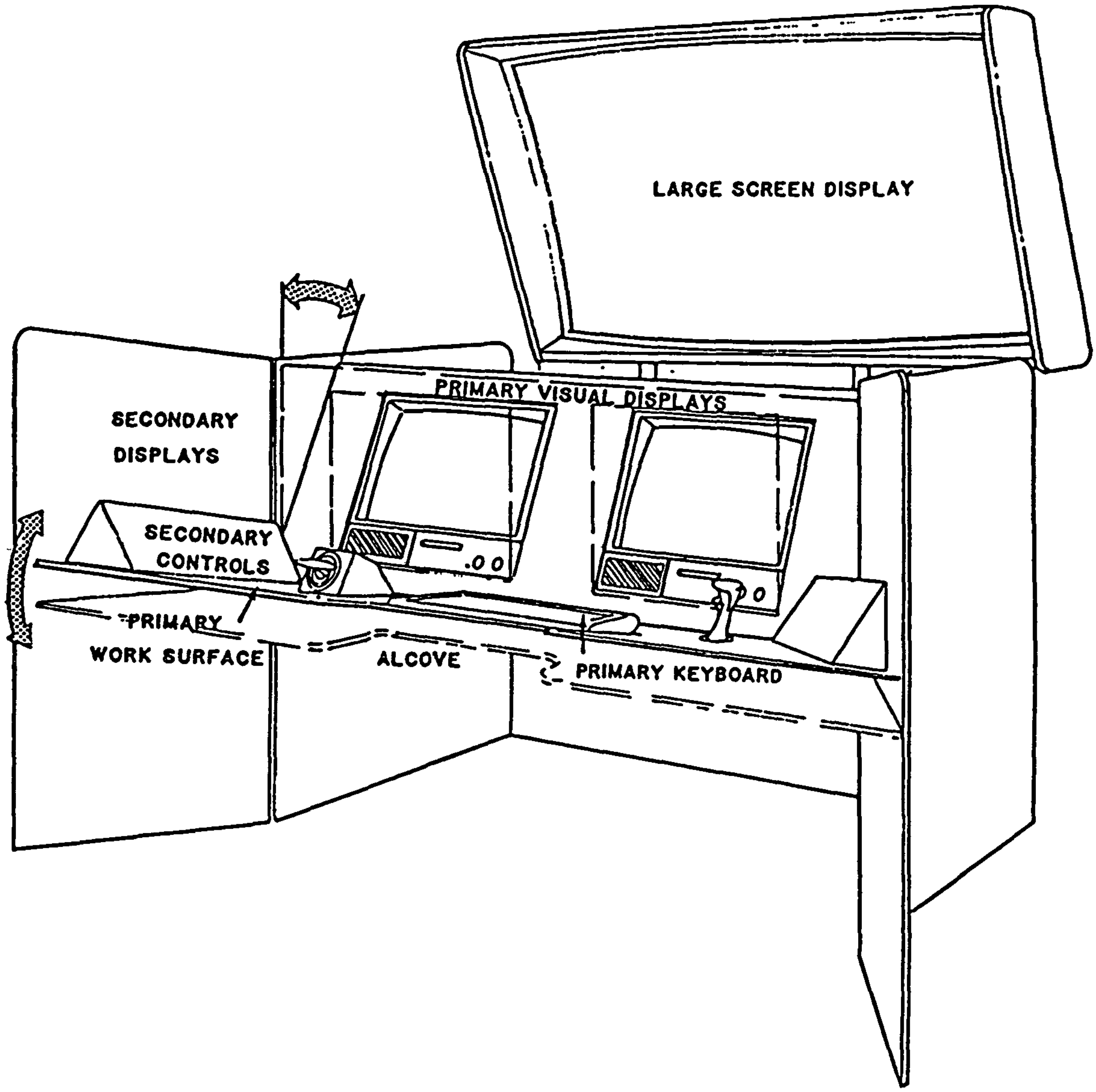

Figure 1.3: The Reconfigurable Workstation

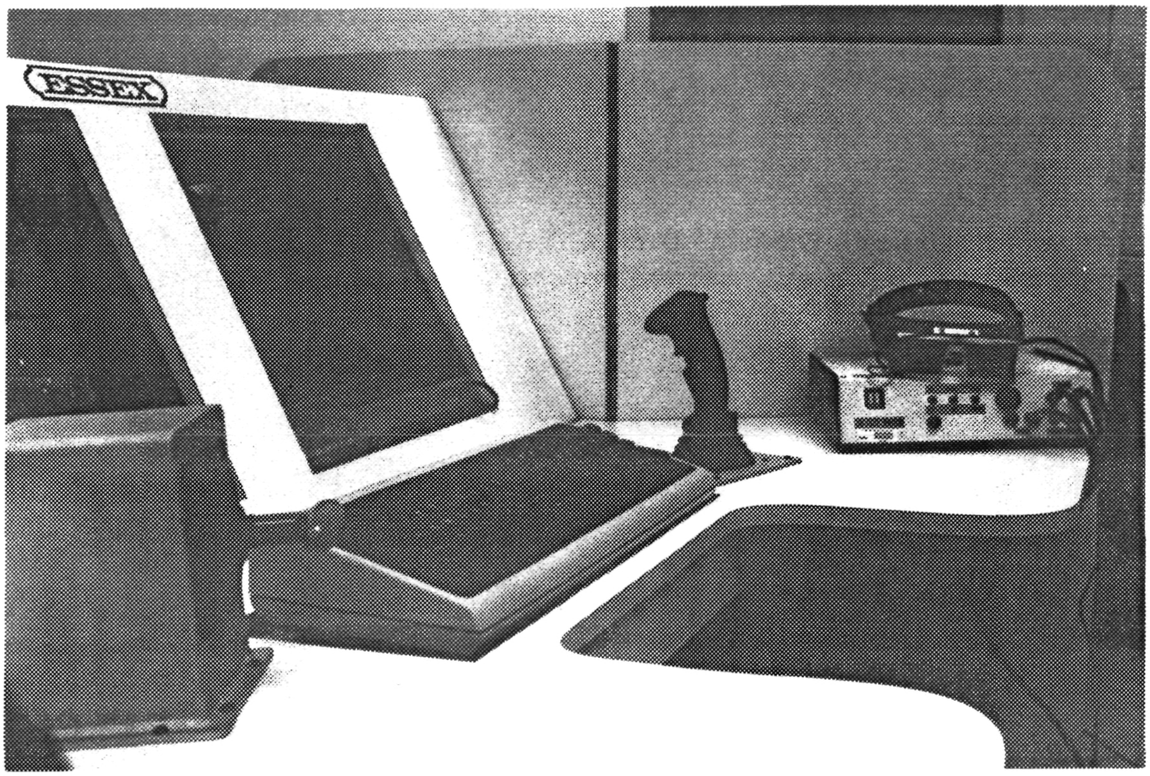

Figure 1.4: The Reconfigurable Workstation Set for a Demonstration of Stereo Vision

Controls

The RWS primary worksurface contains two 3DOF hand controllers and an interactive keyboard. The rotational hand controller (Measurement Systems, Inc., model 544-G308) is located on the right side of the RWS primary worksurface. This controller actuates the TOM-B pitch, roll, and yaw functions. A four-way thumb switch located on the rotational controller operates the pan and tilt unit for the TOM-B perimeter camera. The translational hand controller (Measurement Systems, Inc., model 544-G510) is located on the left side of the RWS. This controller actuates the X, Y, and Z axes of the TOM-B.

For check-out or demonstration purposes, the TOM-B may also be controlled from the engineering console located in the flat floor equipment rack (Drawing No. 35636-01). This 19-inch rack contains two 3DOF joy sticks and two monitors.

The auxiliary controls currently in use are toggle switches and thumb wheels. Four, two-way, momentary toggle switches are located on the left RWS auxiliary control panel (Figure 1.5). These switches are configured to remotely operate the iris of the TOM-B bore sight camera and the zoom, focus, and iris of the perimeter camera. Three thumb wheels, located to the right of the workstation, allow selection of the images displayed on the three RWS monitors. The interactive keyboard is an RCA Data Terminal (model UP4801), located in the center of the RWS primary worksurface. A three-position trigger, a miniature joy stick, push buttons, and a bar switch are located on the rotational hand controller and are available for future control configurations.

Command/Telemetry Link

The remote command/telemetry link is shown in Figure 1.6. The Command/Telemetry Unit (CTU) was designed and built by Marshall Space Flight Center, EC33. Documentation on the CTU is available from Fred Roe, EB24. The telemetry portion of this system is not in use at the present time. The command/telemetry system was installed in the facility in an interim configuration in order to proceed with the test and evaluation requirements.

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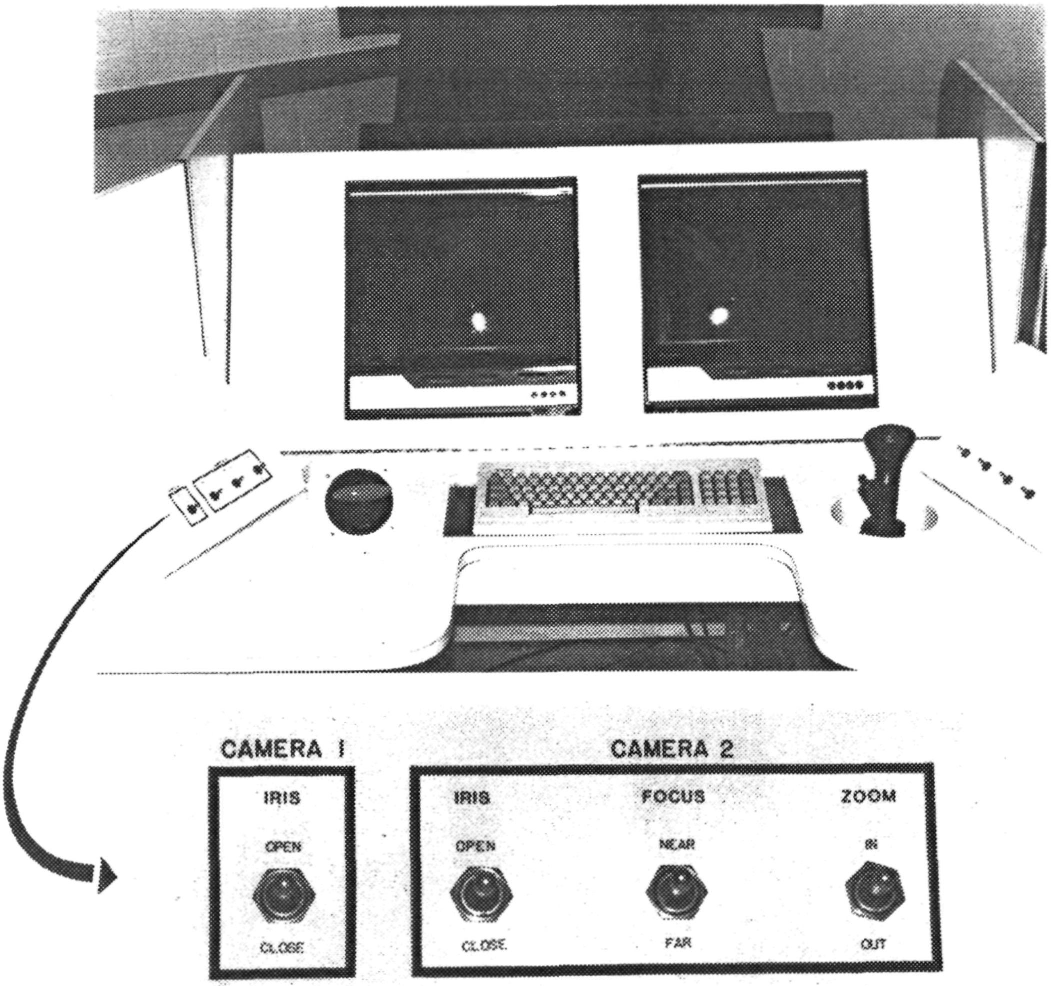
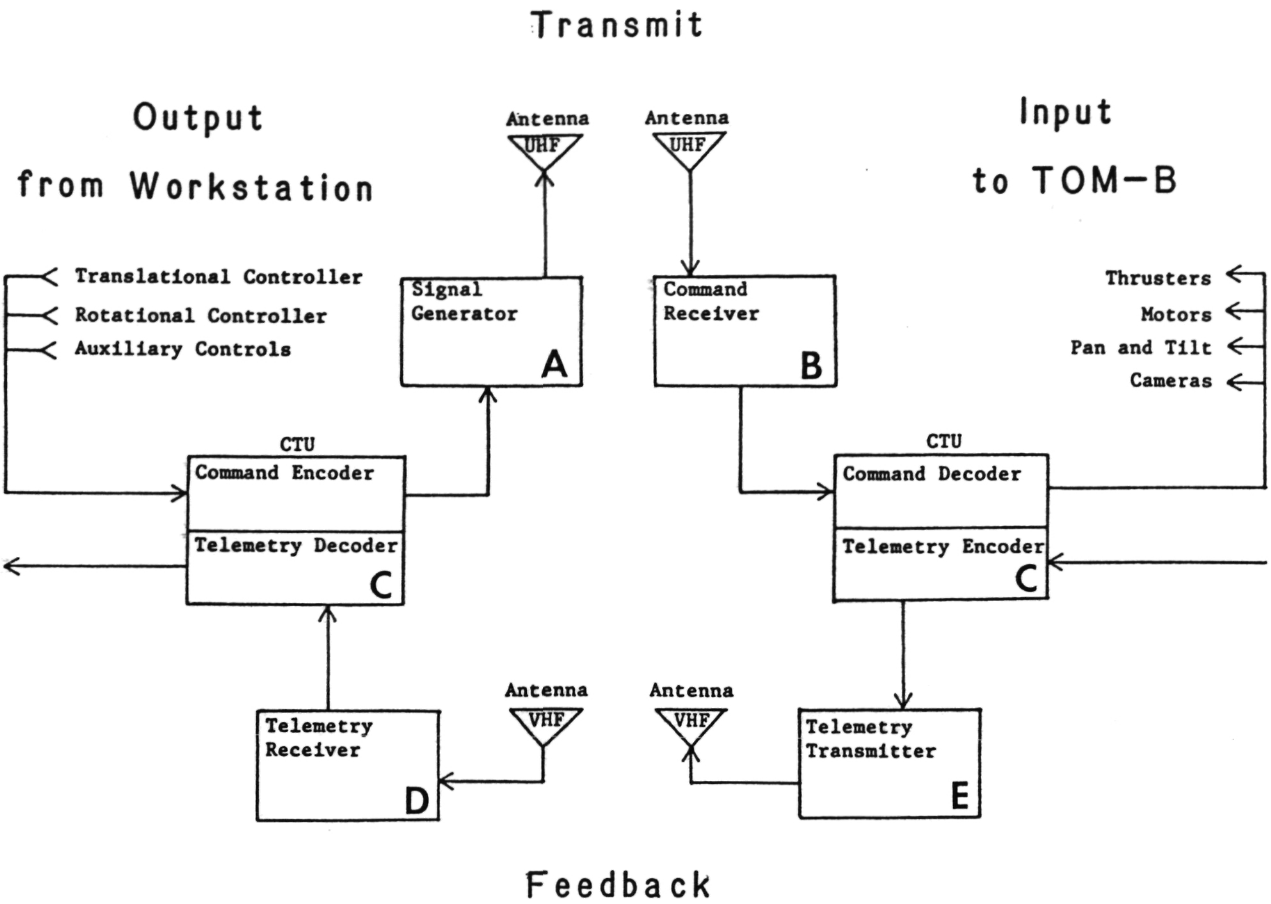


Figure 1.5: Camera Adjustment Controls on the Reconfigurable Workstation Auxiliary Control Panel



Component Specifications	
A	Hewlett Packard HP 8640B
B	Motorola MCR 503-3
C	Command/Telemetry Unit
D	Electro Mechanical Research Inc. Model 2468-01
E	Defense Electronics Inc. Model TR-711

Figure 1.6: Teleoperator and Robotics Evaluation Facility Command/Telemetry System

2.4 Target/Docking Systems

Three mock-ups have been used to simulate docking targets or remotely piloted vehicles in the TOREF: the aft end of the Hubble Space Telescope (HST), the Multi-Mission Modular Spacecraft (MMS), and the Orbital Maneuvering Vehicle (OMV). Docking mechanisms are available to interface with each of these mock-ups

Hubble Space Telescope (HST)

The HST is a full-scale mock-up of the aft end of the flight HST. The mock-up is mounted at the east end of the flat floor at a height compatible with TOM-B docking mechanisms. The aluminum-framed, paper-covered, lightweight mock-up has three hard-mounted docking points as well as a standard Remote Manipulator System (RMS) docking target. The HST is mounted on a rigid stand; however a small yaw and pitch capacity and a continuous 360 degree roll are built into the mounting stand. The HST, shown in Figure 1.9, may also be mounted on the DTS.

Multi-Mission Modular Spacecraft (MMS)

The MMS (Figure 1.9) is a full-scale mock-up of a module which is incorporated in some spacecraft designs, such as the Solar Maximum Satellite. The lightweight, aluminum-framed, paper-skinned mock-up is currently mounted on the DTS. The mounting plate is also compatible with the TOM-B, TMSS, and HST stand mounting plates. The MMS is equipped with three hard docking points and an RMS docking target.

Orbital Maneuvering Vehicle (OMV)

A full-scale mock-up of the OMV (Figure 1.9) is available for laboratory use. This generic mock-up may be mounted on the TOM-B, DTS, and HST stand. The OMV is equipped with a mount for the RMS end effector and an RMS grapple fixture. The OMV may be used as a target or as a remotely operated vehicle.

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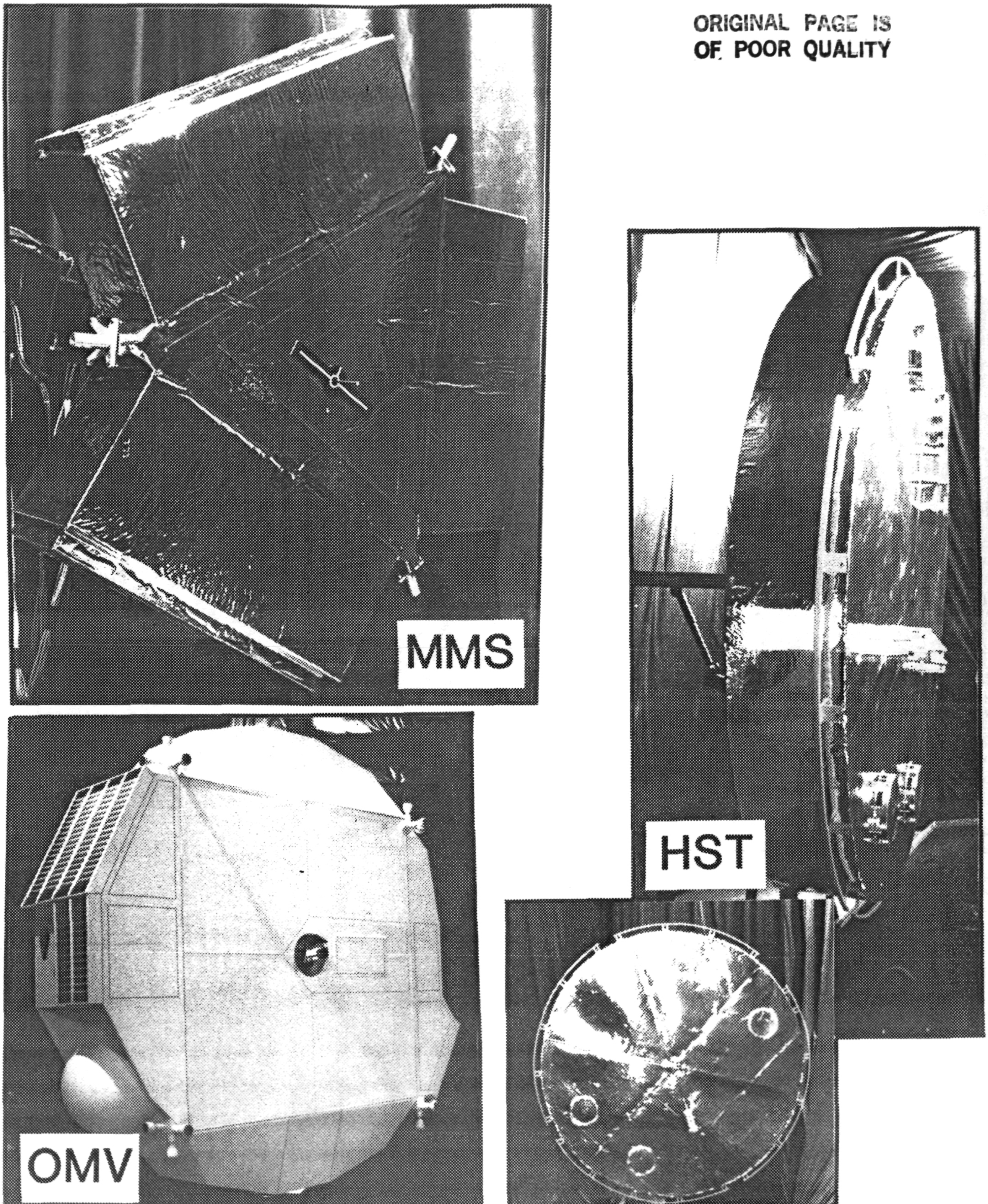

Figure 1.9: Hubble Space Telescope (HST), Multi-Mission Modular Spacecraft (MMS), and Orbital Maneuvering Vehicle (OMV) Mock-ups

Docking Mechanisms

The MSFC Three-Point Capture Device is currently mounted on the TOM-B (Figure 1.10). The Capture Device is compatible with the HST and the MMS. Also available are an RMS end effector, an Essex Three-Claw Docking Mechanism, and a Docking/Retrieval Mechanism. The RMS end effector may be mounted on the TOM-B or the DTS for docking with the OMV mock-up.

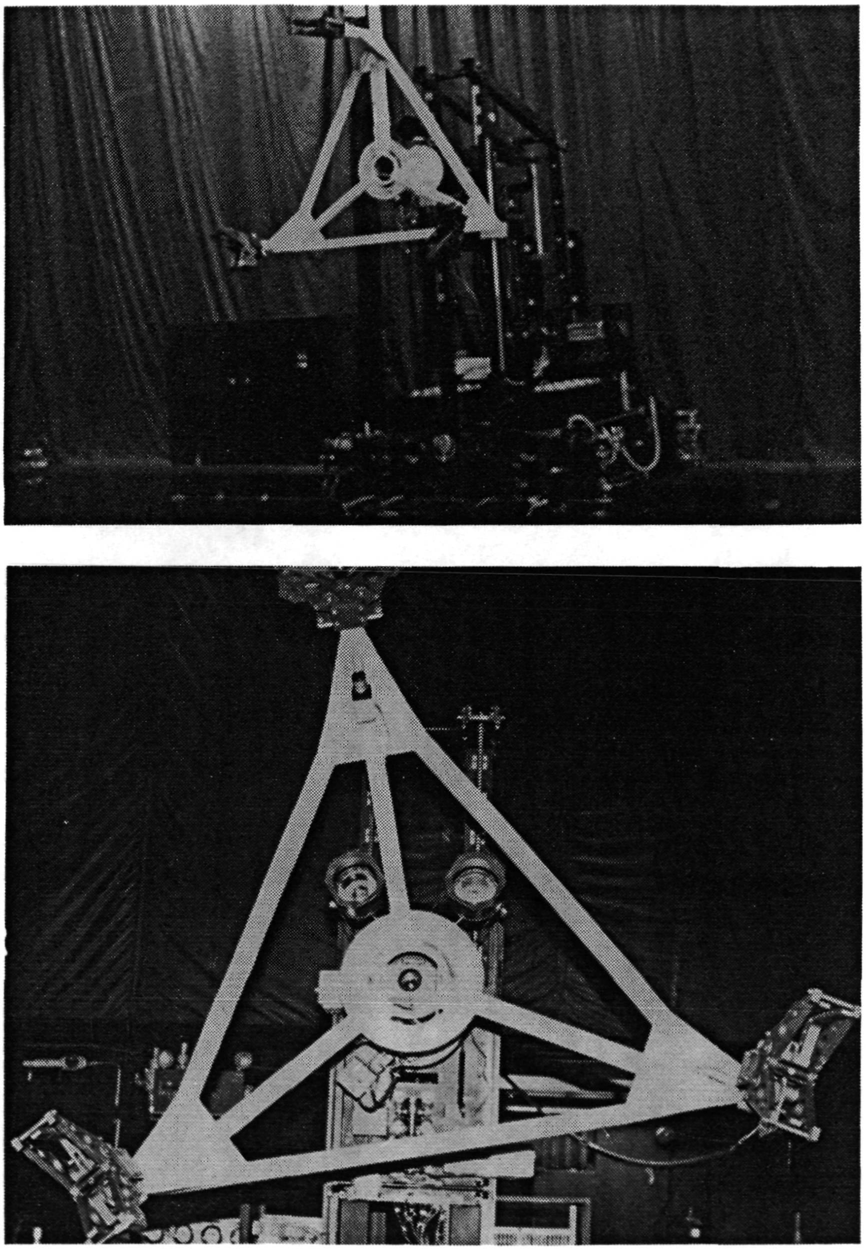

Figure 1.10: Three-Point Capture Device Mounted on the Teleoperator Motion Base

2.5 Data Collection and Recording Systems

A VAX 11/750 computer is provided for real-time simulation and for data collection and analysis. This computer is equipped with a high speed printer and keyboard connections.

Video may be recorded with a Panasonic Portable VHS recorder (NV-8420) and camera. A Panasonic Omnivision II VHS recorder (NV-8950) is also available for use with any of the laboratory cameras.

2.6 Communication System

The laboratory communication system was manufactured by Clear Com Systems Inc. The system provides two-channel voice communication between the flat floor safety technician, test conductor, and flat floor equipment monitor.

The power supply for the communication system is located in the flat floor equipment rack (Drawing No. 35636-01). This supply powers connection/intercom boxes located on the equipment rack and on the flat floor and control room patch panels. Multiple headset connections are provided by these boxes. The communication system is documented in Drawing No. 35636-05 and 35636-06.

Five headsets are available in the laboratory. The safety technician's headset is equipped with a cord which allows the technician to communicate from any location on the flat floor. For use during testing or system check-out, a headset is located at the engineering console. A headset is also provided for the test conductor in Control Room 1 with optional connections for the operator or for a technician in the video equipment room.

3.0 DOCUMENTATION

Several of the TOREF subsystems have been documented throughout the text of this report. Additional documentation is included in a drawing package which is appended to this report. A list of the drawings is given below.

Drawing No.	Title
35636-01	TOREF Flat Floor Equipment Rack
35636-02	Visual System Equipment Connections
35636-03	TOREF Approach/Docking Line Camera and Light System
35636-04	Laboratory Surveillance Camera
35636-05	Control Room 1 Communications
35636-06	Control Room Patch Panel #2 and Flat Floor Patch Panel #1

The System Integration and Verification Testing of an Orbital Maneuvering Vehicle for an Air Bearing Floor

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PART 2 FACILITY OPERATIONS

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1.0 INTRODUCTION

In order for test personnel to reach appropriate levels of data production and data analysis at the TOREF, efficient and safe operation of the equipment and systems in the laboratory is essential. The delicate and dangerous nature of the laboratory systems dictates a thorough working knowledge of all system components, human/system interfaces, and system/system interfaces. Inexperienced or untrained personnel should be prohibited from operating any of the TOREF equipment. Specific areas of concern include the motion systems, support equipment, control room equipment, and protection and maintenance of the flat floor.

2.0 MOTION SYSTEMS

The motion systems include the TOM-B, TMSS, and the DTS. Safe operating procedures and routine maintenance are required for each system.

2.1 Teleoperator Motion Base (TOM-B)

To create dynamic motion simulation capabilities, the TOM-B is powered by high-pressure pneumatics and high-amperage electronics. Improper use or neglected maintenance of this system could cause injury to operators or damage to system components.

Pneumatic System

All TOM-B pneumatic fittings should be secure before tank filling is attempted. Fittings should be checked for leaks and tightness on a weekly basis.

Two fill ports with individual shutoff valves are located on the rear of the TOM-B, and the vehicle can be refilled in approximately 10 to 15 minutes from the flat floor service area. The ports, one for the thruster system and one for the air bearing pad system, can be filled separately or together. Pressure gauges are provided for each tank system. The pneumatic system fill ports, gauges, and hand loaders are shown in Figure 2.1.

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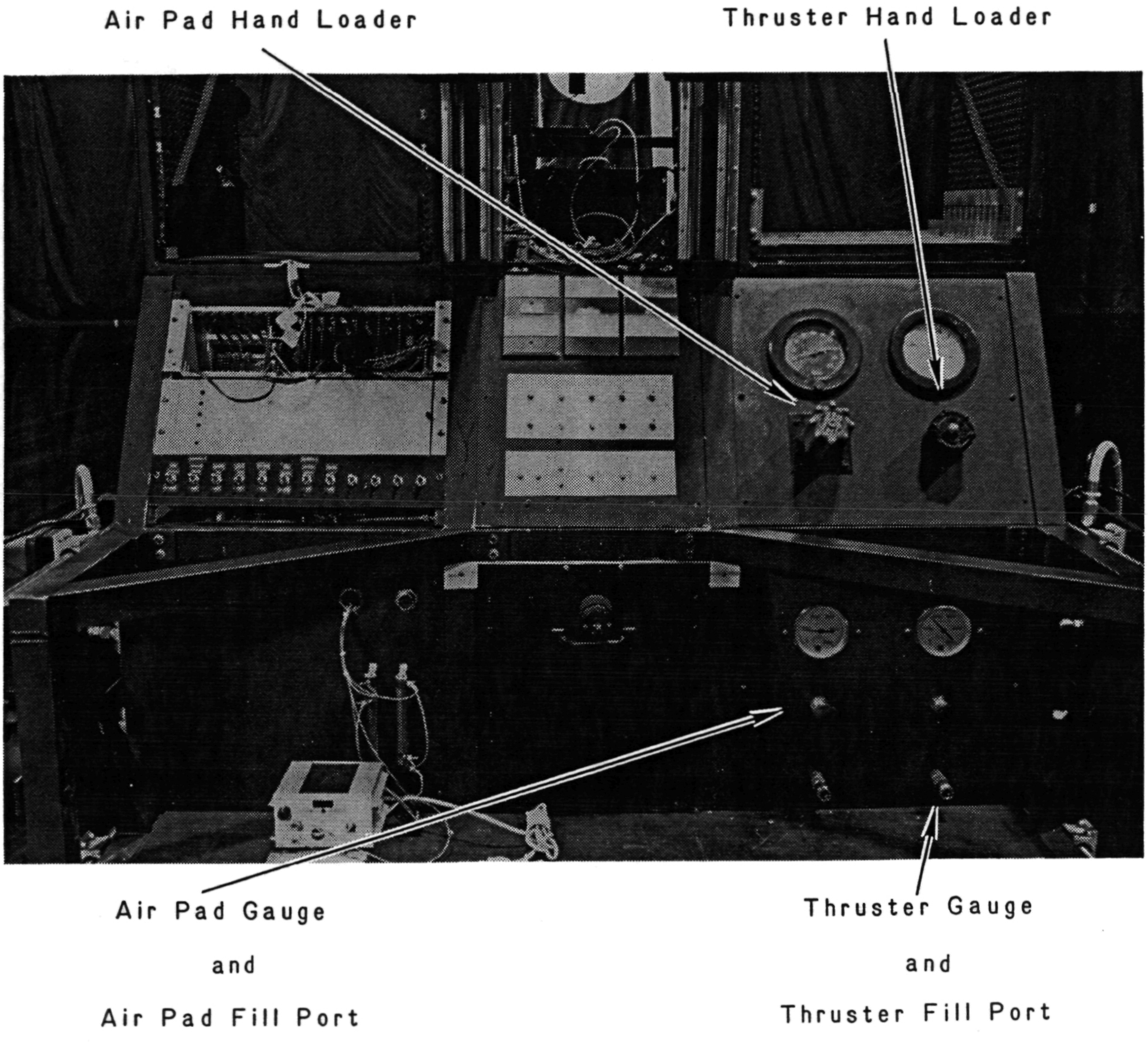

Figure 2.1: Teleoperator Motion Base Pneumatic System Fill Ports, Gauges, and Hand Loaders

The procedure for refilling the TOM-B air system is as follows:

1. Purge air panel connecting lines and close purge valve.
2. Set air panel dome loader to 3,000 psi (or a lesser desired pressure).
3. Couple armored air panel connecting lines to TOM-B fill ports.
4. Open TOM-B thruster and air pad system shutoff valves.
5. Open shutoff valve to air panel connecting lines.
6. Allow tanks to fill to desired level (maximum = 3,000 psi).
7. Close shutoff valve to air panel connecting lines.
8. Close TOM-B thruster air and air pad system shutoff valves.
9. Purge connecting lines, leaving purge valve open.
10. Uncouple connecting lines and stow.

High pressure air (up to 3,000 psi in this system) can be very dangerous. Any deviation from the tank filling procedure may result in injury to laboratory personnel. In case of a line failure, close all fill valves immediately.

When performing routine line checks on TOM-B plumbing, fill plumbing system with desired pressure and close valves to TOM-B tanks. This allows for a high pressure leak inspection with a small volume of air in the plumbing system. In the event of a ruptured line during inspection, this procedure would limit the amount of escaping air flow and the risk of injury to lab personnel.

For further pneumatic system information, see Contract NAS8-34726 Final Report No. H-85-04.

Electrical System

Standard caution observed around electrical systems should be used when charging the TOM-B battery bank system or when working on the TOM-B electrical wiring system.

The battery bank system is designed to facilitate charging with one plug for all three battery banks. The procedure for charging the system is as follows:

1. Turn TOM-B power off.
2. Plug charging system cable into TOM-B receptacle, turn clockwise, and lock.
3. Turn all charging system power supply voltage and current controls to zero.
4. Turn on the three charging system power supplies.
5. Adjust Bank No. 1 charger to ≤30 VDC, ≤10 amps.
   Adjust Bank No. 2 charger to ≤36 VDC, ≤12 amps.
   Adjust Bank No. 3 charger to ≤30 VDC, ≤10 amps.
6. When current levels drop to 1-3 amps, batteries are charged.
8. Turn off all charging system power supplies.
9. Unlock and unplug charging system cable and stow.

All electronic devices on TOM-B are wired with a common ground to the aluminum frame of the TOM-B. Because of this, any positive voltage applied to the TOM-B ground or frame may damage the electrical system. For further electrical system information, see Contract NAS8-34726 Final Report No. H-85-04.

TOM-B Operating Procedures

Initial Start-Up and Check-Out Procedures

1. The facility air handlers should be on unless a test run is in progress. If the air handlers are not on, they should be turned on at the breaker box located behind the flat floor equipment rack (Breaker No. 29).
2. Place flat floor equipment rack breaker No. 34 in the "on" position.
3. The signal generator should be set at 450 MHz and locked.
4. The pneumatic system of the TOM-B should be filled according to the procedures in Section 2.1.

5. After all control room start-up procedures have been completed, the power switch on the TOM-B control panel (Figure 2.2) should be placed in the "on" position.
6. Place the following toggle switches on the TOM-B control panel in the "on" position: motors, thrusters, transmit, receive, video 1, video 3, aux 1, and aux 2.
7. Complete a check-out from the flat floor area. Fire thrusters and move the motors from engineering console and move the pan and tilt unit from the TOM-B.
8. Complete a check-out from the control room. Fire the thrusters, move the motors, and move the pan and tilt unit from the RWS.
9. Place the power and video 3 toggle switches in the off position until test runs begin.

Test Run Procedures

1. Turn off air handlers and the light above the equipment rack.
2. Turn air pad hand loader to 40-55 psi and thruster air hand loader to 100 psi. DO NOT exceed these values.
3. TOM-B should be pushed to the test run starting position. The TOM-B air pads SHOULD NOT come into contact with the edge of the flat floor.
4. For dark-side runs, the flood and spot toggle switches should be placed in the "on" position.
5. Battery and air levels should be continually monitored by the safety technician when the TOM-B is in operation. Power levels may by read from the control panel meters (Figure 2.2). Voltages should not be allowed to drop significantly below the charged levels. Amperage readings should not exceed 2.5 amps. The pad air system should not be allowed to drop below 200 psi. <u>The amount of air in the pad system must be continually monitored.</u> If the pad air system level drops below 100 psi, the TOM-B could become stranded on the flat floor. If levels are not as specified, the TOM-B should be returned to the service area for check-out or maintenance.

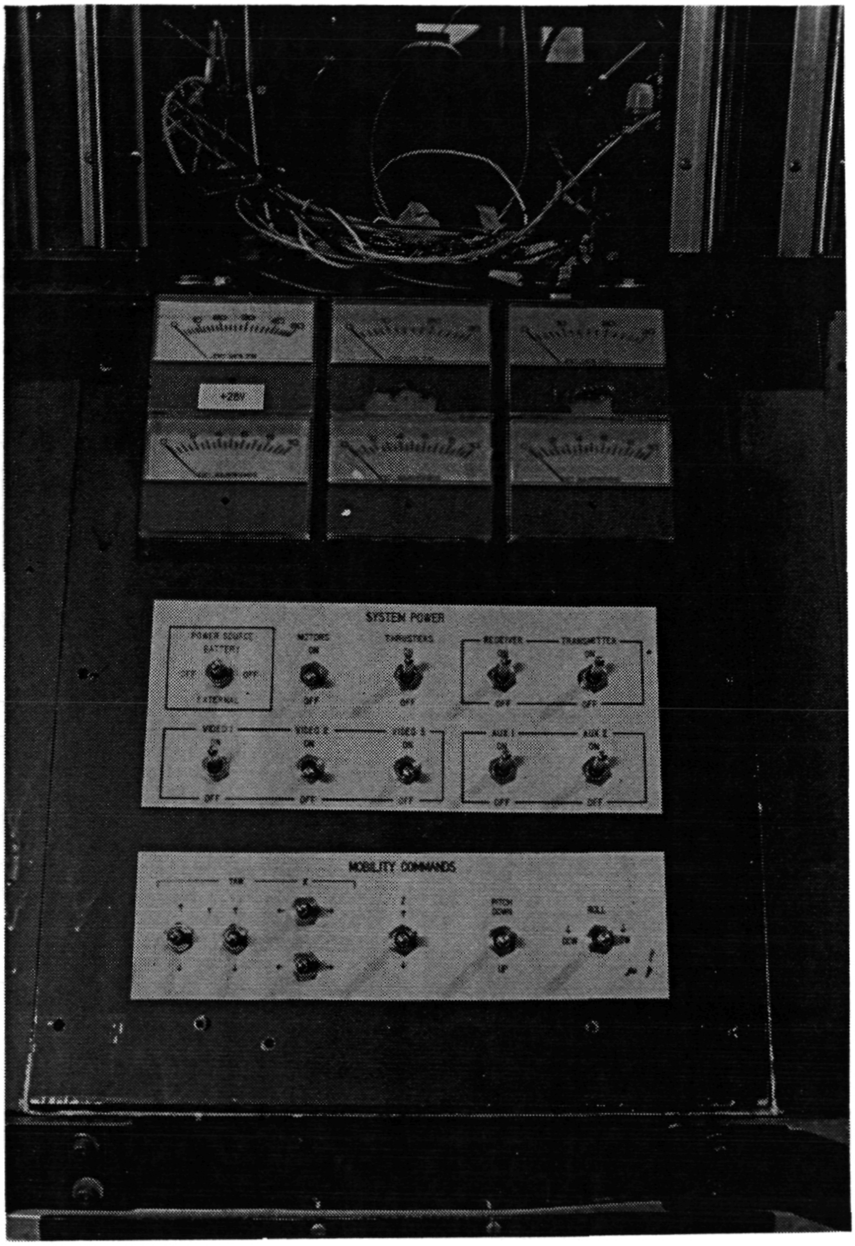

Figure 2.2: Teleoperator Motion Base Control Panel

Shut-Down Procedures

1. The TOM-B should be returned to the service area.
2. The air pads should be down loaded to 0 psi.
3. All toggle switches should be placed in the off position.
4. The air handlers should be turned on.
5. The flat floor equipment rack should be turned off.
6. The light above the equipment rack should be turned on.
7. All other flat floor lights should be turned off.

2.2 Target Motion and Support Simulator and Dynamic Target Simlator

The TMSS is powered by pneumatics and electronics. The same safety and maintenance practices observed with use of the TOM-B should also be applied to use of the TMSS and DTS. Procedures for operating the DTS are available from Marshall Space Flight Center, EB 24.

3.0 SUPPORT EQUIPMENT

All support equipment should be turned on 30 minutes prior to check-out procedures to allow for equipment stabilization. All equipment should be turned off before leaving the TOREF.

3.1 Flat Floor Equipment Rack

The flat floor equipment rack is turned on at the breaker box located behind the rack. Specific equipment settings are as follows:

H.P. Signal Generator	Frequency	= 450.00 MHz
Left Microwave Transmitter	RF	= 2287
	Local OSC	= 2205
Right Microwave Transmitter	RF	= 2223
	Local OSC	= 2145
Upper H.P. Power Supply	VDC	= 28
Lower Kepco Power Supply	VDC	= 5

3.2 Visual System Equipment Rack

The visual system equipment rack is turned on by inserting four plugs into the sockets of an extension cord. Standard care and maintenance of the electrical cords and sockets should be followed. The video connections in this rack are given in Drawing No. 35636-02. Additional information about the capabilities and operation of this system is available from Daryl Craig, EB 23.

3.3 Auxiliary Cameras

Approach/Docking Line Camera

The toggle switch on the power supply located under the approach/docking camera should be placed in the "on" position. This will turn on the approach/docking light in addition to the camera. The reading on the power supply should be 28 VDC. Care should be taken to insure that the TOM-B does not come in contact with the approach/docking light or the power supply.

Control Room Camera

The control room camera is activated by placing the toggle switch on the Panasonic power supply in the "on" position. The power supply is located next to the visual system equipment rack.

Flat Floor Surveillance Camera

This camera is activated when the flat floor equipment rack is turned on. Display images are presented on the center monitors when the appropriate channel is selected.

3.4 Command/Telemetry

The CTU, located in the Computer Room, is powered by a Kepco regulated power supply located adjacent to the CTU rack. Voltage readings taken from the terminals at the back of the CTU should be 5 VDC, ± 0.25.

4.0 CONTROL ROOM

All control room equipment should be turned on at least 30 minutes prior to a test run in order to allow equipment power levels to stabilize. All monitors should also be turned on at this time. Picture selection should be made with the three thumb wheels located at the right side of the RWS. The RWS primary worksurface and monitors can be adjusted by carefully loosening the clamps on the supporting shocks, moving the worksurface and/or monitors, and carefully tightening the clamps. No excessive weight (including equipment) should be placed on the RWS primary worksurface. All control room equipment should be turned off prior to leaving the TOREF.

5.0 FLAT FLOOR PROTECTION AND MAINTENANCE

Protection of the flat floor is an absolute necessity for TOREF operation. The thin film of air escaping from the air bearing pads on the TOM-B and TMSS must have a smooth, flat surface on which to ride. Scratches and indentations in the epoxy flat floor can disrupt the ability of the motion systems to float on the flat floor. Methods to repair epoxy air bearing floors have been unsuccessful in the past; this increases the necessity of keeping the floor free of any damage.

5.1 Protection

The 4,000-square-foot epoxy surface, known as the flat floor, was applied by Essex Corporation in 1983. The care and maintenance of this surface is critical to its usefulness as a test bed. There is no demonstrated way of repairing this surface if it becomes damaged. The epoxy used in preparing the flat floor is still elastic and will remain so for at least the next ten years. Samples poured by Essex in 1975 still show elasticity, and the technical documentation on the epoxy suggests that it will become 98% cured in 20 years. For this reason, loads should not be placed on the flat floor for extended periods of time. This will result in depressions on the floor which will "capture" the air bearing pads of the TOM-B. For periods of extended rest, the TOM-B should be removed from the flat floor or moved daily from one position to another on the service pad area.

No vehicle, other than precision floating vehicles, should ever be permitted on the flat floor surface. No wheeled carts or trolleys should be allowed on the floor. If there is a need to move equipment onto the floor, equipment can be placed on the available suspension bridge which spans the floor.

Never permit overhead work to be conducted without suitable protection for the flat floor. Even changing light bulbs involves the risk of ladders or glass bulbs falling on the floor, either of which could irreparably damage the floor surface.

Personnel required to walk upon the floor must wear clean room booties over flat-soled tennis shoes (not over bare feet or street shoes). It is preferable that persons who will be serving as safety technicians reserve a pair of tennis shoes strictly for this purpose. The requirement to have people walk on the epoxy surface should be kept to an absolute minimum.

When servicing the TOM-B, it should always be placed in the service pad area or removed from the flat floor. If maintenance is conducted in the flat floor service area, the floor underneath should be draped if fluids are being used or if mechanical systems are being moved or altered. If there is drilling or any activity that may leave scraps in the TOM-B, the scraps should be blown out with low pressure air to make sure that no foreign material makes its way to the epoxy floor surface.

5.2 Maintenance

Accumulated dust can interfere with the operation of the TOM-B as it floats only one thousandth of an inch above the flat floor surface. Consequently, the floor should be damp mopped with alcohol at least once a week when not in use and before every test session when in experimental use. The floor should be mopped with soft floor mops covered with non-lint cloth, the whole of which has been dampened with 190 proof alcohol. When debris has been picked up on the cloth, it should be replaced immediately with clean cloth. The pattern for cleaning (up and down or back and forth, etc) should be changed periodically so that the patina does not run only one way on the floor. The area around the flat floor should be completely vacuumed every week, and foreign material should be cleaned up immediately.

The System Integration and Verification Testing of an Orbital Maneuvering Vehicle for an Air Bearing Floor

Contract NAS8-35636
Final Report
February 22, 1986

PART 3 VERIFICATION TESTING

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1.0 INTRODUCTION

The purpose of the second phase of the Integration/Verification contract was to conduct a pilot test series to demonstrate the readiness of the Teleoperator and Robotics Evaluation Facility to support investigations in the area of remote operations and to obtain useful results and conclusions generic to the use of remotely controlled space vehicles. In order to address a current need for data, the test series focused on information necessary for the design of the Orbital Maneuvering Vehicle (OMV). Although the test series revolved around the OMV, the data obtained contribute to the general fund of knowledge on the subject of human operation of remotely managed systems.

The test series began in September 1984 with a study comparing the Reconfigurable Workstation (RWS), which was designed by Essex under a separate contract (NAS8-35473) for use in the TOREF, with a conventional workstation. The research effort was then suspended to allow Essex engineers to modify the Teleoperator Motion Base (TOM-B) motor drive and air system under contract NAS8-34726 so that the motion base would be capable of fulfilling the requirements of an OMV simulation which arose after the original TOM-B was constructed. The test series was restarted in February 1985 with an investigation concerning the OMV on-board lighting system and continued until January 1986. During this period, a variety of research methods were used to investigate the issues of OMV camera location, lighting requirements, camera pointing, field-of-view, camera lens control by the operator, video bandwidth reduction, the utility of stereo vision, and ground control station specifications.

The objectives of this section of the contract final report are to give a summary of the findings from the verification test series, to provide a detailed synopsis of each test conducted, to outline issues for future research, and to provide an extensive bibliography for each topic investigated in this test series for use by future researchers.

This research effort was conducted under the direction of Nicholas Shields Jr., Essex Teleoperator and Robotics Program Manager. Mr. Shields has been involved in the Teleoperator Technology Development Program at MSFC for the past 14 years. Mary Frances Martin served as test conductor and was responsible for experimental design, data collection and analysis, and publication of test results. Working with Ms. Martin were Crystal D. Sulyma and Karen R. Paulukaitis. Ms. Paulukaitis and Ms. Sulyma were instrumental in data analysis and report publication as well as being responsible for TOREF facility operations. David E. Henderson designed the TOREF systems necessary for remote operation of the TOM-B and was responsible for system trouble-shooting throughout the test program. John W. Haslam, Jr. designed much of the Essex hardware in the laboratory and was responsible for test-specific hardware design, fabrication, and installation.

2.0 VERIFICATION TEST PROCEDURES

The experimental philosophy employed in the design of the test procedures was to use a small number of test subjects, who were well-trained on a standardized task, in a within-subjects design with repeated measures. This philosophy was adopted based on the fact that the OMV operators will be extensively trained through the use of simulations. In addition, the use of experienced subjects maximized the available training/testing time and minimized the effects of learning on test results. The within subjects type of experimental design and statistical analysis with repeated measures take into account the variability in each individual's performance which is not a result of the influence of the independent variables. This type of analysis determines where statistically significant differences occur while adjusting for the random variability which is inherent in human task performance. In this experimental design, each subject makes several test runs under all of the experimental conditions. The analysis of variance (ANOVA), which is employed to test for significant performance differences, is calculated using the mean of each subject's scores on the dependent variables. An alpha level of .05 was used to determine statistical significance throughout the test series. Differences which reached significance at the .10 level were considered statistical trends.

All test subjects were NASA employees. The subjects were given the Federal Aviation Administration (FAA) examination for visual acuity at the NASA Medical Center. Only subjects who had normal visual acuity (or acuity corrected to normal) participated in the test series. Additionally, selected body dimensions were measured to insure that all subjects were within the 5th to 95th percentile size range of the U.S. population. The subjects' average age was 28.3 years, and the number of men and women who participated in the tests was approximately equal.

Subjects were trained using a successive approximation technique. This type of training increases the difficulty of the task performed in small steps. First, the general operation and purpose of the TOREF was explained to the subject. The subject then used direct vision to operate the TOM-B from the flat floor engineering console. The operation of the RWS remote hand controllers was demonstrated, and the subject operated each TOM-B axis of motion independently in order to learn the precise outcome of each input on the remote visual image. The subject then practiced an approach and docking task under normal laboratory lighting until their performance stabilized. Prior to each test session, the subject made one to three "warm-up" runs under these conditions.

The apparatus used in the tests has been described in Part 1 of this report. Briefly, the TOM-B and the Three-Point Capture Device constituted the basic OMV simulator. The simulator was equipped with cameras and lights as required for each test. Subjects controlled the motion base from the RWS with two 3DOF hand controllers. The target chosen for these tests was the HST aft end mock-up. This mock-up and the Three-Point Capture Device were selected for the baseline system because HST retrieval is one of the OMV design reference missions. The capture device and target are shown in Figure 3.1.

An approach and docking task was designed for use throughout the test series. The task began with the motion base placed at the west end of the flat floor and aligned with the HST target. This alignment was chosen based on the assumption that the OMV approach control mode would have achieved translational alignment with the target at the simulator-to-target distance available on the flat floor (21.3m). Due to the nature of the test design, the TOM-B pitch and Z motor axes were set at docking alignment during the first test in the series. In the remaining tests, the Z axis was offset +20cm from ideal alignment and the pitch axis was offset +5 degrees at the beginning of each run.

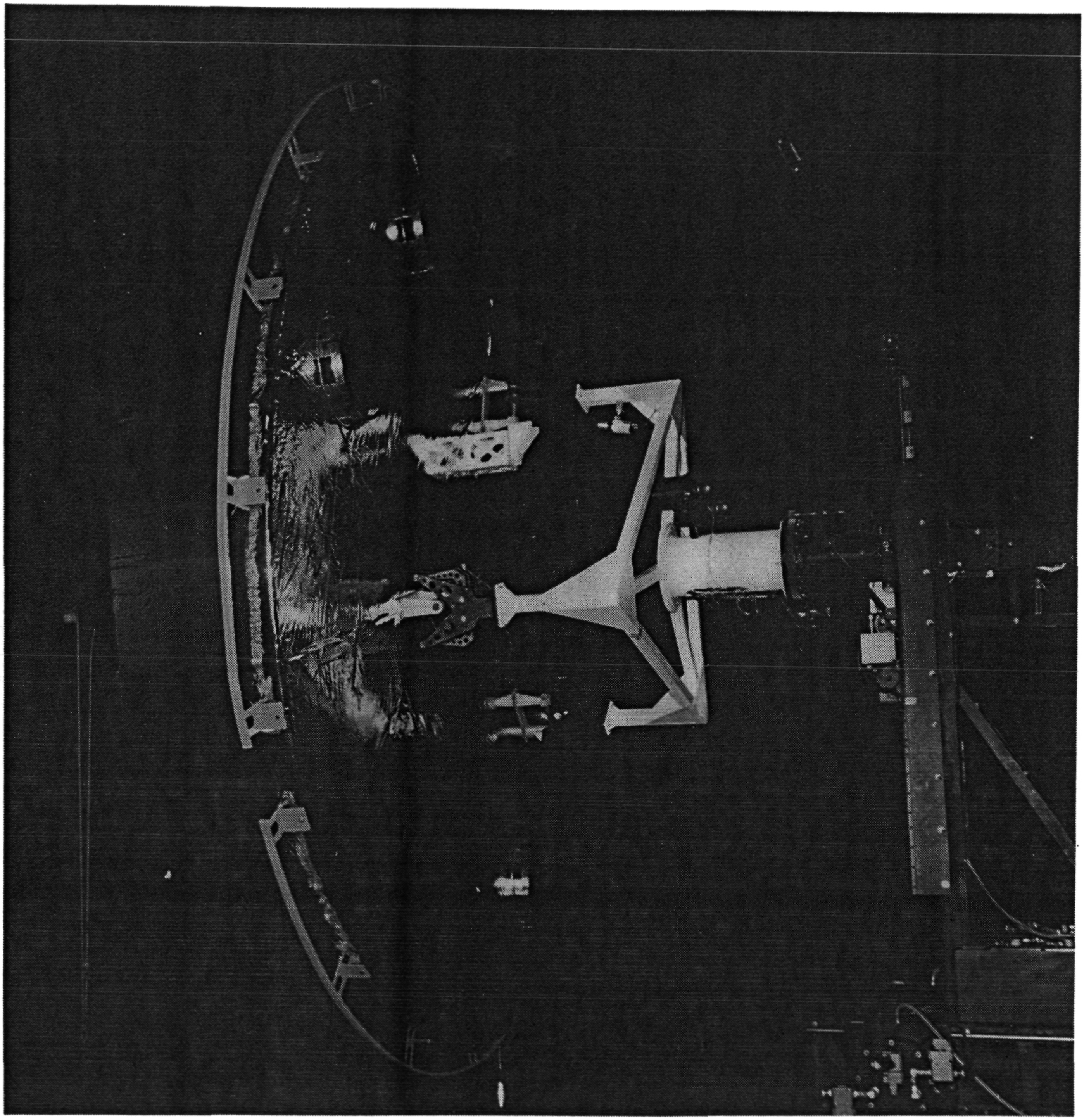


Figure 3.1: Three-Point Capture Device Docked with the Hubble Space Telescope Aft End Mock-up

An optimal translational alignment angle with respect to the target was empirically determined by measuring the distance that the capture device claws could be off alignment with the HST docking pins and still make a successful dock. Motion base movements outside this angle were termed translational errors. The time required to reenter the alignment angle was termed translational error recovery time. The flat floor available maneuvering distance (21.3m) was divided into approach and docking zones. The first 75 percent of the range to the target (16.0m) was designated as the approach zone and the remaining distance to the target (5.3m) was called the docking zone. The alignment angle and approach/docking zones are shown in Figure 3.2.

The subject's task was to place the simulator in motion on a signal from the test conductor, approach, and attempt to dock with the target. In all tests, a successful dock was defined by the entrance of the HST docking pins into all three of the capture device claws (Figure 3.3). The only information provided to the subject during test runs was visual feedback from the simulator cameras and start/stop signals from the test conductor. Task illumination was provided by the overhead facility lights for tests conducted under daylight conditions or by lights on the simulator for tests in dark-side conditions.

The dependent measures were thruster air expended, elapsed run time, frequency of translational errors, translational error recovery time, and Z and pitch axes alignment. Instructions to subjects emphasized successfully docking with the target and achieving a balance between accuracy, air consumption, and elapsed time.

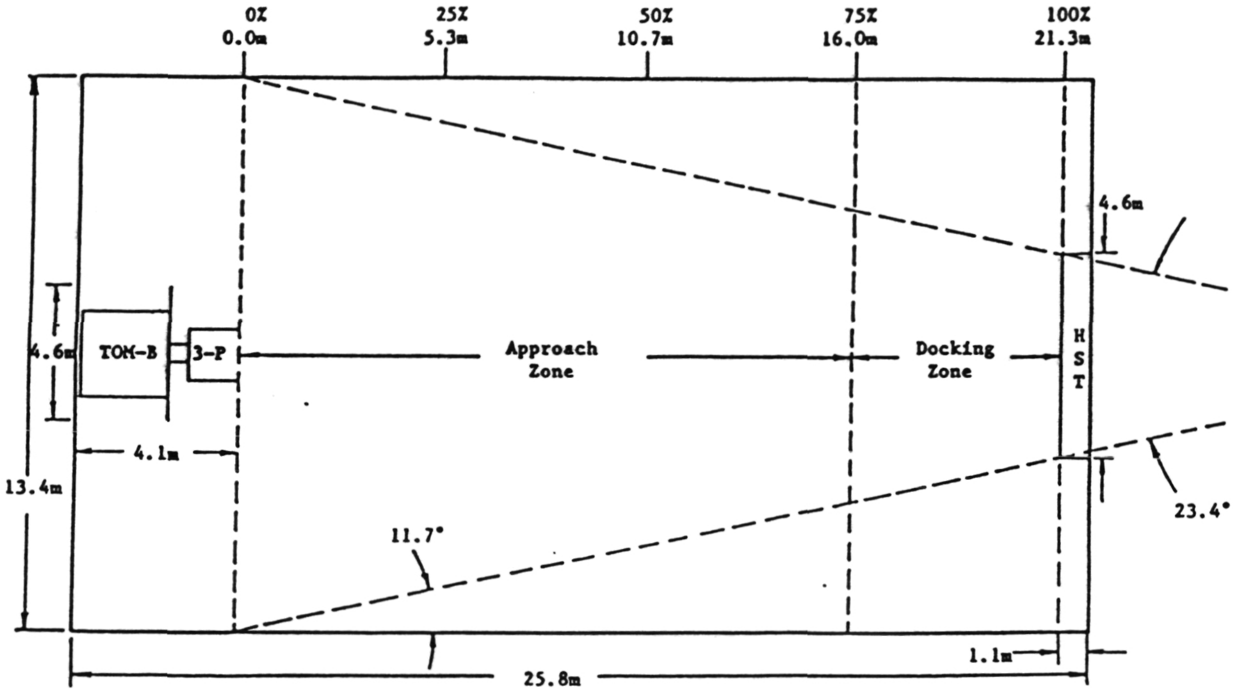


Figure 3.2: Flat Floor Available Maneuvering Distance, Alignment Angle, and Approach/Docking Zones

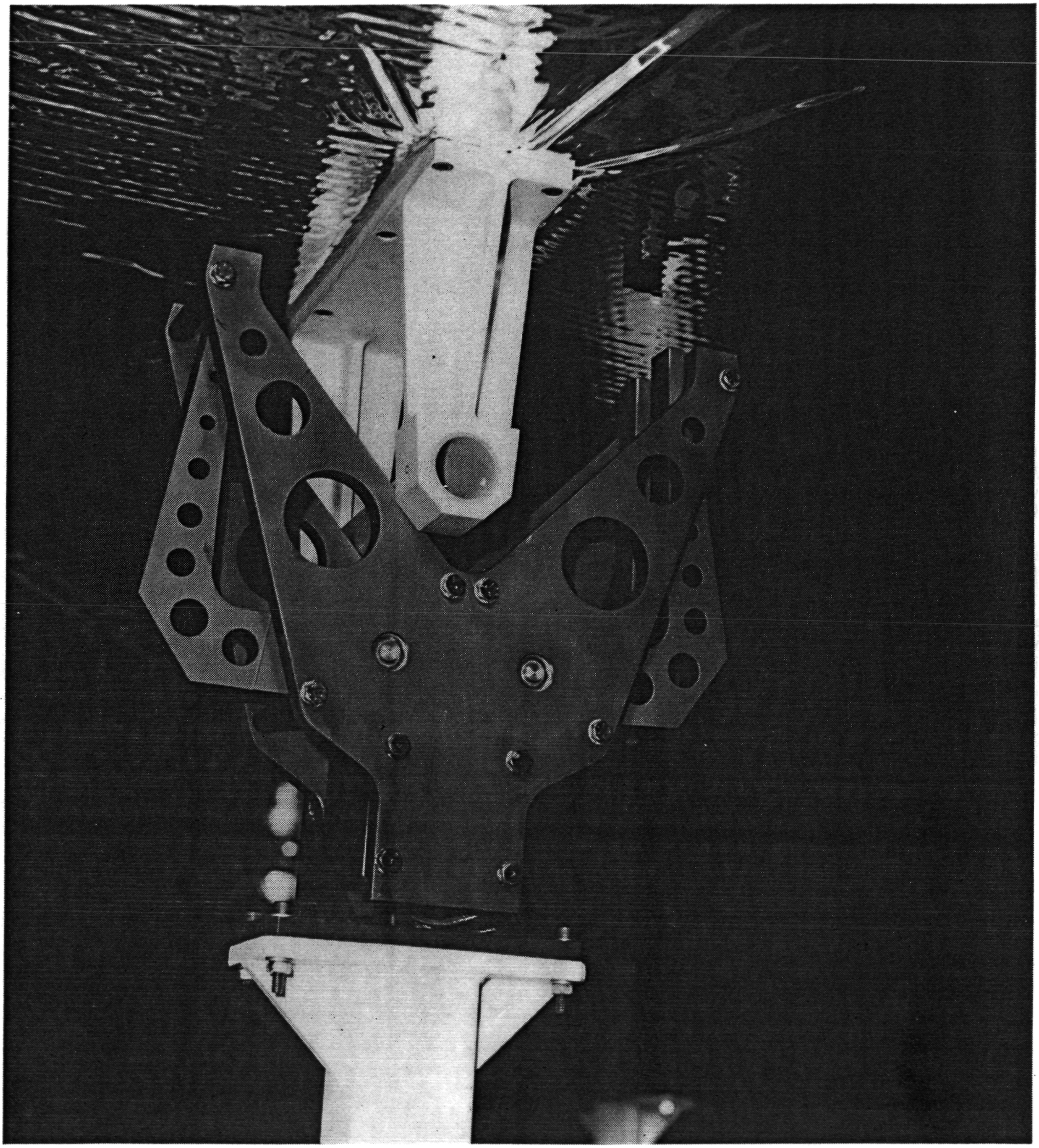


Figure 3.3: Hubble Space Telescope Docking Pin and Three-Point Capture Device Claw in Docked Position

The following publications document the results of the investigations conducted during the verification test series. The main findings from these tests are summarized in Section 3.0.

Martin, M.F., Shields, N.L., Jr., & Rodriquez, R.C. (1984). The Reconfigurable Workstation, short task comparative analysis (Test Report No. 11-84-RWS-01). Huntsville, AL: Essex Corporation.

Martin, M.F., Young, D.G., & Sulyma, C.D. (1985). OMV approach and docking with onboard flood or spot lights (Test Report No. 03-85-OMV-01). Huntsville, AL: Essex Corporation.

Martin, M.F., Sulyma, C.D., & Haslam, J.W., Jr. (1985). OMV camera location: A preliminary investigation (Test Report No. 04-85-OMV-02). Huntsville, AL: Essex Corporation.

Martin, M.F., Sulyma, C.D., & Paulukaitis, K.R. (1985). Lighting requirements for two OMV camera locations, revision A (Test Report No. 06-85-OMV-03-A). Huntsville, AL: Essex Corporation.

Martin, M.F. & Paulukaitis, K.R. (1985). OMV vision systems: (A) Field-of-view and light intensity (B) Operator control of zoom, focus, and iris (Test Report No. 10-85-OMV-04). Huntsville, AL: Essex Corporation.

Martin, M.F. & Paulukaitis, K.R. (1986). OMV operation with reduced video frame rate (Test Report No. 11-85-OMV-05). Huntsville, AL: Essex Corporation.

3.0 EXECUTIVE SUMMARY OF VERIFICATION TEST RESULTS

This section summarizes the research findings obtained during the verification test program. This program focused primarily on the OMV visual system. Some aspects of the visual system are specified in the OMV Requirements Document, Revision 2 (1985). This document states that the OMV Communications and Data Management Subsystem (C&DM) shall include cameras and lights necessary to accomplish docking and payload viewing under full daylight or dark side conditions. The Requirements Document further specifies that a minimum of two cameras will be included in the C&DM and that at least one camera will have pan, tilt, and zoom capabilities. One goal of the verification test series was to conduct investigations regarding these minimum visual system requirements and to establish visual system design criteria which will optimize operator performance.

Camera Location

The results of Test No. 04-85-OMV-02 indicated that a centrally-located camera, which bore sighted a docking target, combined with a camera located at the outer perimeter of the OMV enhanced operator performance. This conclusion was supported by previous research and by observations throughout the remaining tests.

Camera Field-of-View

The effects of field-of-view (FOV) on remote operator performance were investigated through a review of the past research on the use of fixed and variable FOV (optical zoom) in the performance of target acquisition tasks. Based on the available information, it was recommended that a camera lens which provided a 4 to 55 degree variable FOV under operator control be considered for inclusion in the OMV visual system.

Iris, Zoom, and Focus Control

Test No. 10-85-OMV-04-B was conducted to investigate the effect of placing the iris, zoom, and focus of the OMV perimeter camera lens and the iris of the bore sight camera lens under operator control. The addition of these controls to the operator's workload did not significantly affect performance of the approach and docking task. The results indicated that the addition of the lens controls tended to improve performance during approach operations. Control of the camera iris was helpful in reducing overly bright monitor images caused by light reflected off the target surface.

Camera Pointing Control

Performance on the approach and docking task with and without pan and tilt was compared in Test No. 06-85-OMV-03-A. The frequency of translational alignment errors and the time required to recover from misalignment increased significantly with the addition of pan and tilt. It was concluded that these differences would be eliminated by additional practice with the pan and tilt function. The pan and tilt capability proved advantageous in a series of simulated bore sight camera failure runs.

Type of Lights

Results of an initial lighting investigation (Test No. 03-85-OMV-01) indicated that a combination of flood and spotlighting would improve operator performance of the approach and docking task under simulated dark-side conditions. This conclusion was supported by results from additional testing.

Light Location

Location on the OMV of individual lights was not used as an independent variable in the test series. Test No. 06-85-OMV-03-A was conducted primarily to investigate optimal beam widths; however, the results also indicated that locating a light with the camera on the pan and tilt unit was useful to the operators by allowing them to point the light and illuminate target features for translational alignment. A light was also located with the bore sight camera throughout the dark side tests in the series and provided adequate illumination for this camera image.

Light Beam Width

Four floodlight and four spotlight beam width combinations were investigated in Test No. 06-85-OMV-03-A. Performance of the approach and docking task under dark side conditions was enhanced by the use of a floodlight combination of an 80 x 20 degree beam width at the bore sight camera location and a 40 x 7 degree width at the pan and tilt perimeter camera location. Performance was degraded by the use of two 80 x 20 degree floodlights and two 5 x 5 degree spotlights. It was concluded that the 80 x 20 degree floodlight at the bore sight location combined with either the 10 x 4 spotlight or the 40 x 7 floodlight at the perimeter camera location should be subject to further evaluation.

Light Intensity

Light intensity was the subject of an empirical analysis in Test No. 10-85-OMV-04-A. Intensity of two beam width combinations (an 80 x 20 degree floodlight at the bore sight camera location with either a 10 x 4 degree spotlight or a 40 x 7 degree floodlight at the perimeter camera location) was varied during an approach and docking scenario. The resulting luminance of both camera images on the remote monitors was measured and compared with standards drawn from previous human factors research. The monitor images were also evaluated for subjective picture quality. Results of the evaluation indicated that monitor luminance between 95 and 350 candelas/square meter (cd/m^2) would present satisfactory visual cues to the operator.

Stereo Vision

An extensive literature search was conducted on the topic of stereoscopic (stereo) vision and visual systems. Fourteen sources were reviewed, most of which compared remote task performance using stereo display systems with monoscopic (mono) display systems. Based on the information obtained from the available research, the conclusion was made that a mono system with two orthogonal views would be most appropriate for use with the OMV. As a whole, the research did not indicate a clear enough performance advantage to offset the increased cost, complexity, and bandwidth required for a stereo, as opposed to mono, system.

Frame Rate

OMV operation with reduced frame rate video feedback was investigated in Test No. 11-85-OMV-05. It was concluded that use of a 5 frames/second (fr/s) transmission rate would not affect OMV operator performance if the resolution and gray scale were not degraded below normal levels. It was recommended that frame rates between 5 and 3 fr/s should be subject to further investigation in conjunction with the use of optical zoom and command time delay.

Resolution and Gray Scale

Equipment was not available to vary resolution and gray scale for evaluation in Test No. 11-85-OMV-05. A review of previous research on bandwidth reduction revealed that a video system which provided 3.75 fr/s, 256 x 256 pixels/frame resolution, and 1 bit of gray/pixel did not significantly affect performance of a target acquisition task using a remotely piloted vehicle. Because the conditions in these studies were analogous to OMV operation, it was concluded that a system of this nature should be investigated for the OMV visual system.

Ground Control Station

Guidelines for the design of the OMV ground control station were developed based on the results of Test Report No. 11-84-RWS-01 and on observations made throughout the verification test series. The workstation should be designed to accommodate and optimize the performance of a wide range of operators. The 5th percentile oriental female through the 95th percentile U.S. male anthropometry standard was recommended as the appropriate guideline. The worksurfaces and displays should be adjustable to individual operator preference. Keyboards should be located for bilateral operation and adjustable with respect to the primary worksurface. Full forearm support should be provided for hand controller operation. Provisions should be made for secondary displays and controls within the nominal reach envelope and visual cone of the 5th percentile operator; however the number of secondary tasks required of the primary operator should be limited.

4.0 SYNOPSES OF VERIFICATION TESTS

Presented in this section is a synopsis of each test and evaluation conducted under the Verification Test Program. The objectives, background research, apparatus, methodology, results, and conclusions of each investigation are summarized. The apparatus and methodology of all tests were similar and are described in Section 2.0. Apparatus and methodology which differed from this general test procedure are specified in each synopsis.

4.1 OMV Approach and Docking with Onboard Flood or Spot Lights

Test Report No. 03-85-OMV-01

The purpose of this test was to investigate the effects of flood and spotlighting on operator performance of an OMV approach and docking task under dark-side conditions. The null hypotheses were that the dependent variables (run success, thruster air consumption, elapsed time, translational error frequency, and error recovery time) would not differ significantly due to the type of light (flood or spot), the zone of operation (approach or docking), or an interaction effect.

The OMV Requirements Document (1985) specified that the OMV lighting system must provide sufficient illumination for payload viewing and docking tasks under full daylight or dark-side conditions. Previous Essex teleoperator evaluations at MSFC (Shields, Piccione, Kirkpatrick, & Malone, 1982) indicated the existence of a dramatic interaction effect between camera line-of-sight, target alignment, and target illumination on docking success. Researchers also found that on-board floodlighting was effective for illuminating target shapes and spaces which were otherwise obscured by shadows in solar illumination conditions (Shields & Henderson, 1981).

Seven subjects were chosen for training, and subsequently five were chosen to participate in the test based on training performance. The two women and three men ranged in age from 21 to 39 years.

The TOM-B and the Three-Point Capture device were equipped with a Panasonic, WV-3890B, color camera at the bore sight location and a

Javelin, model JE2062, black and white camera mounted on the top claw of the capture device. A General Electric (GE) 80 x 20 degree floodlight and a 5 x 5 degree spotlight were mounted in adjustable fixtures on either side of the bore sight camera. Location of the cameras and lights is shown in Figure 3.4.

On a signal from the test conductor, subjects maneuvered the simulator toward the HST mock-up and attempted to dock using either the spot or floodlight. Subjects made three test runs with the spot and three runs with the floodlight in a counterbalanced order.

A 2 x 2 x 5 ANOVA (type of light x zone of operation x subjects) was employed for data analysis. Elapsed time differed significantly due to the interaction of type of light and zone of operation, $F(1,4) = 10.79$, $p < .05$. This result was due to performance in the docking zone. The time required to dock was significantly higher under the spotlight condition than under the floodlight condition. There was no difference in approach times. A significant difference in translational error recovery time occurred due to the type of light, $F(1,4) = 13.85$, $p < .05$. Mean error recovery times for approach and docking were lower when the floodlight was used than when the spotlight was used. A trend was evident in thruster air consumption due to the interaction effect, $F(1,4) = 4.58$, $p < .10$. Less thruster air was expended during approach under the spotlight condition than under the floodlight condition, and thruster air consumption for docking was lower under the floodlight condition than under the spotlight condition.

The results indicated that the use of both flood and spotlights should be considered for the OMV visual system. The finding concerning thruster air consumption tended to support the alternative hypothesis that spotlights would enhance approach performance and floodlights would improve docking performance. The elapsed time and translational error recovery time performance also supported this hypothesis, but the results on translational error frequency did not. Subject comments during debriefing indicated that three of the subjects preferred the floodlight while two preferred the spotlight. Those subjects who preferred the floodlight stated that illumination of the target edges aided in realignment when the simulator was yawed with respect to the target, and those who preferred the spotlight said that the position of the spot on the target aided in translational alignment. It was recommended that a combination of flood and spotlights be investigated in conjunction with iris control by the operator.

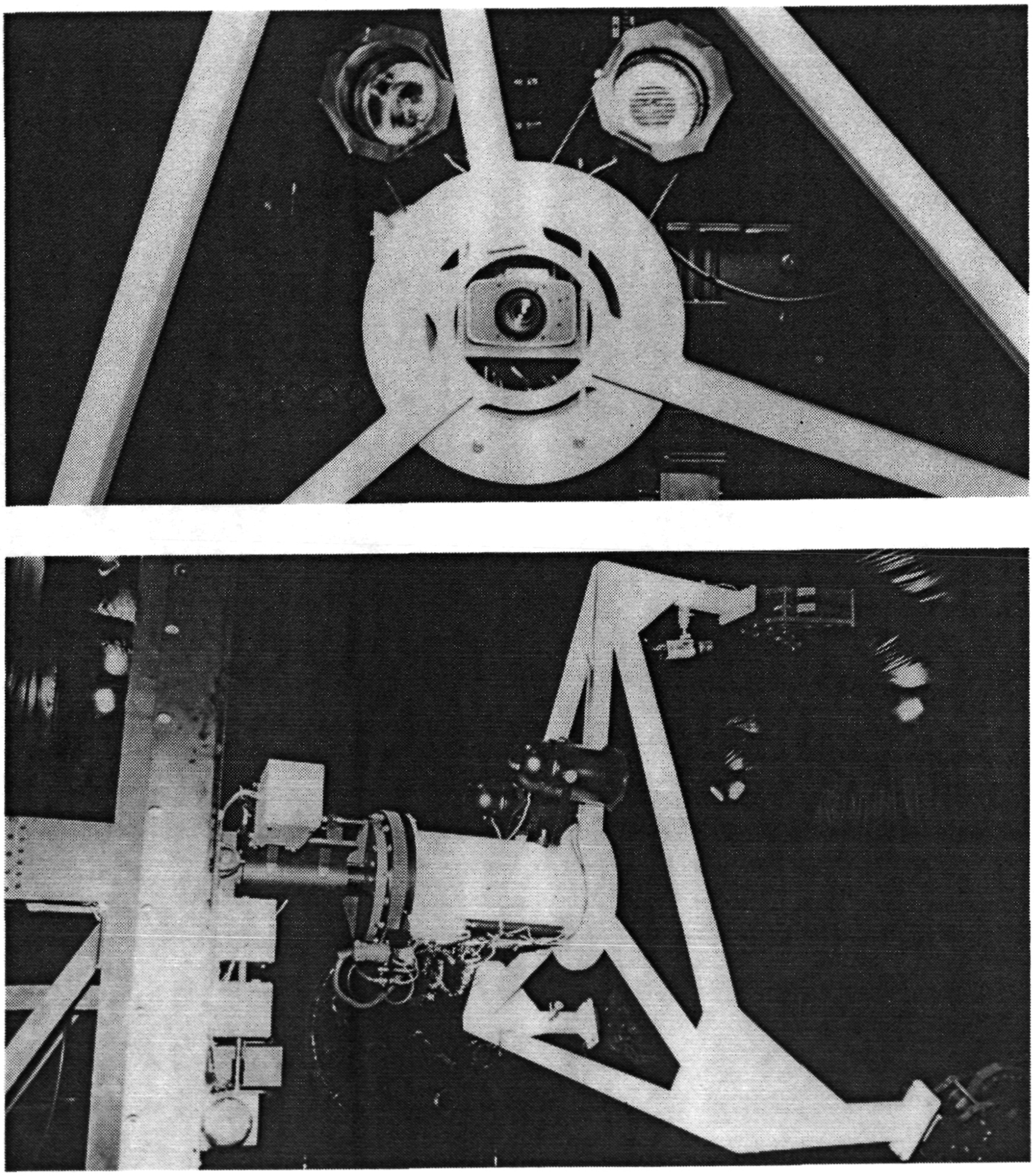


Figure 3.4: The Three-Point Capture Device Position of Lights and Cameras

4.2 OMV Camera Location: A Preliminary Investigation

Test Report No. 04-85-OMV-02

This test was conducted to investigate the effects of OMV camera location on operator performance of an approach and docking task. The null hypotheses were that performance on the dependent variables (thruster air consumption, elapsed time, translational error frequency and recovery time, and alignment of the Z and pitch axes) would not differ significantly due to the camera placement condition.

A search of the NASA Technical Library revealed few studies specifically concerning camera location for teleoperation. Two studies conducted in the former MSFC Teleoperator Laboratory addressed this issue. Shields and Henderson (1981) investigated the effect of Teleoperator Maneuvering System (TMS) camera location on the performance of an approach and docking task. No differences in performance occurred due to the use of a centrally located, bore-sighted camera plus a camera located on the right side of the TMS or a center plus a left side camera. In a similar study, the use of a bore-sighted camera or an off-center, top mounted camera did not significantly affect performance (Shields, Piccione, Kirkpatrick, & Malone, 1982). The two docking mechanisms specified for the preliminary OMV design, the Remote Manipulator System (RMS) end effector and the Three-Point Capture Device (OMV Requirements Document, 1985), necessitate the inclusion of a camera bore-sighted on a docking target. Due to this requirement, a bore-sighted camera was selected for this test as the baseline for the location of additional cameras. A camera located on the capture device, a camera located at the outer perimeter of the OMV, and a boom-mounted camera that would extend approximately 3 feet beyond the perimeter of the OMV have been proposed for the OMV design. These locations were selected for investigation in the present study.

Two women and three men were chosen from the pool of experienced operators. These subjects had participated in the previous test.

Based on the proposed diameter of the OMV (4.75m), the cameras were located as shown in Figure 3.5 to simulate the four possible OMV camera positions previously described. A Panasonic, WV-3890B, color camera was placed in the center of the capture device, and an XES, model 8303, color

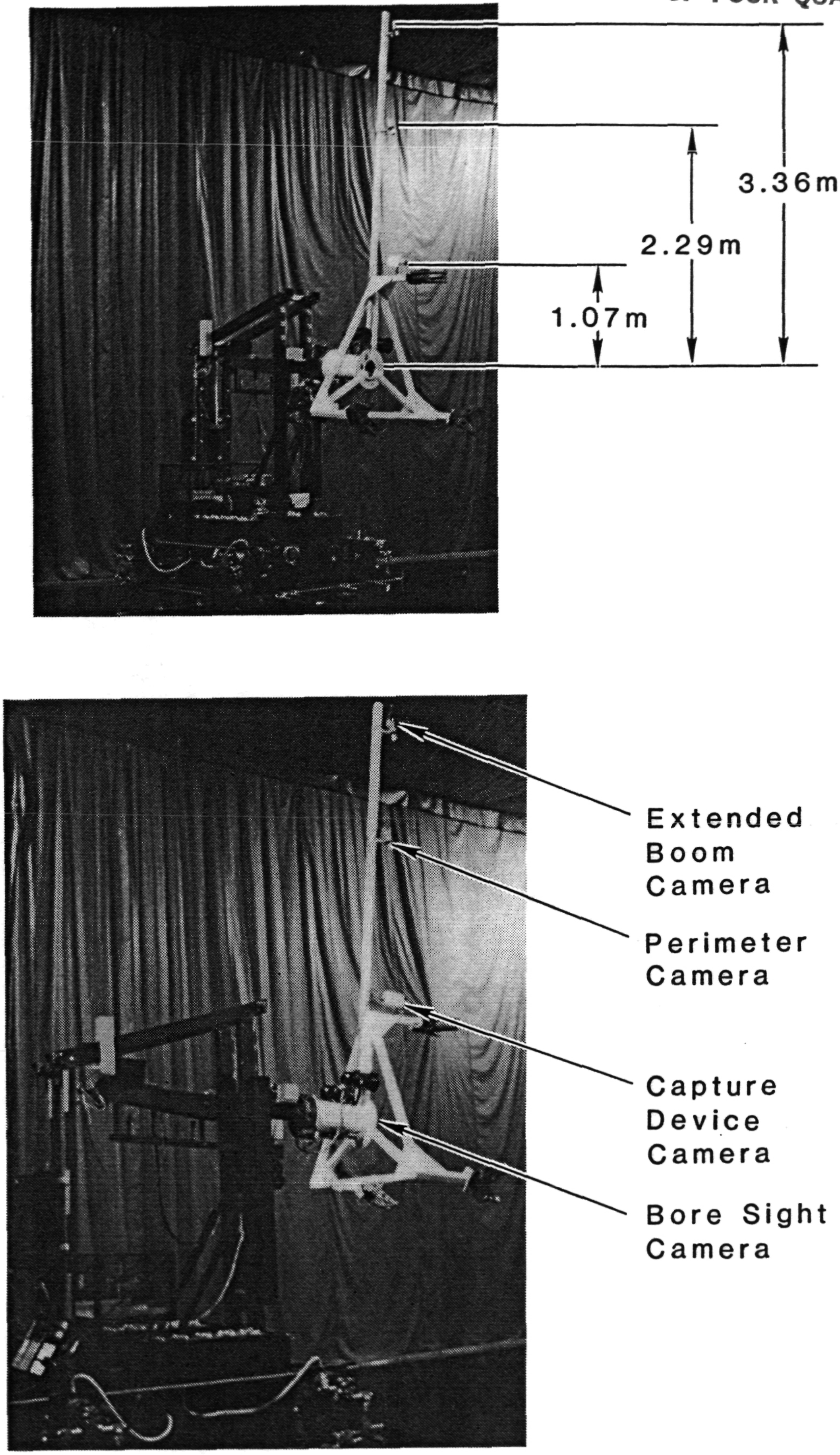


Figure 3.5: Teleoperator Motion Base/Three-Point Capture Device Equipped with Four Cameras

camera was mounted on the capture device claw. The perimeter and extended boom cameras were black and white Javelin miniature cameras, model JE2062. The center camera was bore-sighted on the RMS camera target located in the center of the HST mock-up. This camera provided the subject with a picture of the entire target at the beginning of the run, and it was adjusted so that the camera target was in the center of the monitor when a successful dock was achieved. The capture device camera was focused on the top claw and provided a view of the docking pin as it entered the capture envelope. The perimeter camera and the extended boom camera provided a view of all three claws of the capture device at docking.

Subjects made five runs under four test conditions: bore sight camera only, bore sight plus claw camera, bore sight plus perimeter camera, and bore sight plus extended boom camera. The four test conditions were presented to the subjects in a counterbalanced order. At the beginning of each run, the Z axis was offset +20cm and the pitch axis was offset +5 degrees.

A one-way ANOVA with repeated measures was applied to the data on each dependent variable for approach and docking operations. Thruster air consumption, elapsed time, translational error frequency, and error recovery time were not significantly affected by camera location. Error recovery time tended to be higher and more variable during approach under the capture device camera condition. Error recovery time during docking was most homogeneous under the perimeter camera condition. Alignment of the Z axis was significantly affected by camera location, $F(3,12) = 6.57$, $p < .05$, with alignment being closest to ideal in the perimeter camera condition. Pitch axis alignment tended to be closest to ideal in the perimeter camera condition, $F(3,12) = 3.03$, $p < .10$.

Although a definitive conclusion could not be drawn regarding optimal OMV camera location, the test results indicated that a perimeter camera may enhance performance during docking operations. Alignment of the Z and pitch axes and translational alignment during docking were best when the perimeter and bore sight camera were used. Three of the five subjects preferred this combination, and their performance was consistently better in the perimeter camera condition.

No advantage in performance of the approach and docking task was evident due to the extended boom camera. It was concluded that the additional hardware complexity of this type of camera would not be offset by enhanced performance. The perimeter and bore sight camera combination was recommended for further investigation with added pan and tilt, zoom, focus, and iris control by the operator.

4.3 Lighting Requirements for Two OMV Camera Locations, Revision A

Test Report No. 06-85-OMV-03-A

The objectives of this test series were to assess the effects of adding pan and tilt functions to the OMV perimeter camera and to investigate lighting requirements for OMV perimeter and bore sight camera locations. The pan and tilt test was conducted first so that the pan and tilt function could be used in the lighting test without confounding the results of that investigation. The null hypothesis was that placing the pan and tilt unit under remote operator control would not significantly affect operator performance when compared to the use of a stationary perimeter camera.

Based on the results of Test No. 04-85-OMV-02, an OMV bore sight and perimeter camera were chosen for investigation in this test. The OMV Requirements Document (1985) specified that one of the OMV cameras would have pan, tilt, and zoom capabilities. The perimeter camera was equipped with a pan and tilt unit for evaluation with respect to a stationary perimeter camera in order to investigate the effects of this requirement on operator performance.

Four subjects (two women and two men) who had participated in the previous camera location test were chosen for the pan and tilt evaluation. The fifth subject from the previous test was not available for this evaluation.

A Vicon, model V3000PT, pan and tilt unit was mounted on the vertical extension of the capture device at a distance approximating the outer perimeter of the OMV (2.29m). A Javelin, miniature, black and white camera and two theatrical light fixtures were mounted on the pan and tilt unit. The pan and tilt unit was remotely controlled by the subjects using a four-way, momentary thumb switch located on the RWS rotational hand controller. A control box on the TOM-B allowed test personnel to adjust the pan and tilt unit prior to each run. Location of the pan and tilt unit, lights, and cameras is shown in Figure 3.6.

The four subjects made five test runs under normal laboratory lighting conditions. Prior to testing, operation of the pan and tilt unit was demonstrated to the subjects, and they practiced manipulating the camera with the TOM-B in a stationary position. The pan and tilt perimeter camera was positioned so that the subject had a picture of the entire target at the beginning of each run. The subjects were encouraged to manipulate this camera throughout the run in order to enhance visual cues at a distance as well as to view the docking pins and docking device at close range. The 20 test runs with pan and tilt were compared to the 20 test runs without pan and tilt which were made by the same subjects during the camera location test. After the test runs were completed, each subject made one run under a simulated bore sight camera failure condition. Subjects were not aware that they would lose the bore sight camera picture 16.0m from the target. The test conductor attributed the loss of picture to equipment malfunction and requested that the subject attempt to complete the test run using only the pan and tilt perimeter camera.

The pan and tilt data were analyzed using one-way ANOVAs with repeated measures on one factor. Translational error recovery time during docking increased significantly due to the addition of the pan and tilt capability, $F(1,3) = 47.12$, $p < .01$. Translational error frequency during docking also increased significantly under the pan and tilt condition, $F(1,3) = 25.00$, $p < .05$. No significant differences in thruster air consumption or elapsed time for approach and docking, translational error recovery time or frequency during approach, or in Z and pitch axes alignment at docking occurred due to the addition of pan and tilt. Results of the bore sight camera failure runs were not statistically analyzed. All subjects were able to complete the task using only the pan and tilt perimeter camera with minimal performance degradation.

Performance on two out of the ten dependent variables (translational error frequency and recovery time during docking) was significantly degraded by the addition of pan and tilt capabilities to

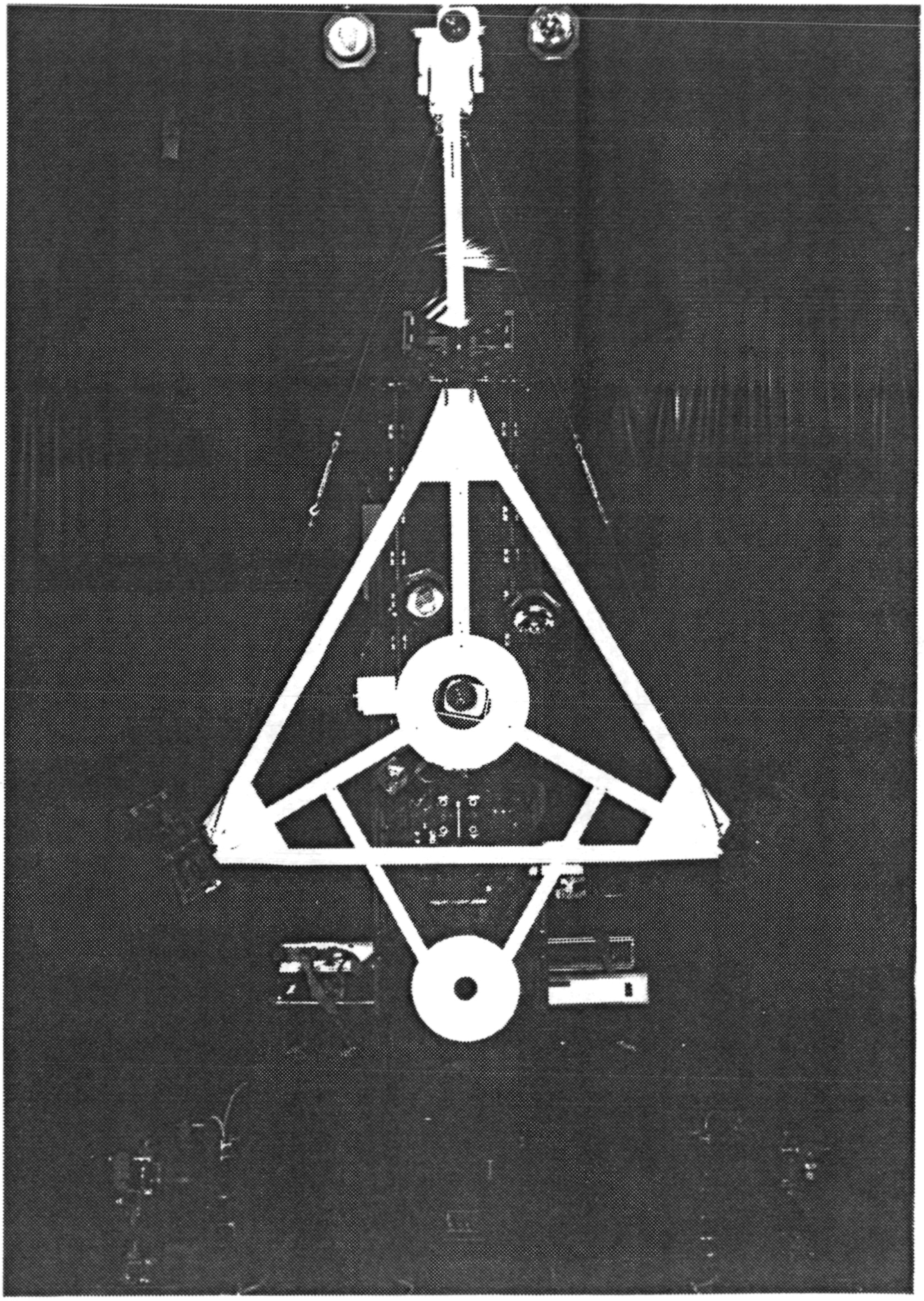


Figure 3.6: Teleoperator Motion Base/Three-Point Capture Device Location of the Pan and Tilt Unit, Cameras, and Lights

the perimeter camera. It was concluded that these differences were due to the additional control activity required during docking. The subjects had to tilt the camera down at approximately 3 to 4m from the target in order to view the capture device/target interface. The subjects were not trained for this addition to their workload. Based on the fact that OMV operators would be highly trained, it was concluded that an OMV pan and tilt perimeter camera would not degrade operator performance. It was also suggested that the ability to point the perimeter camera and lights might enhance performance as well as prevent an aborted mission due to a bore sight camera failure.

The second objective of this test series was to investigate lighting requirements for the OMV bore sight and pan and tilt perimeter camera locations. Four floodlight beam width combinations and four spotlight beam width combinations were employed during the approach and docking task under dark-side conditions. The null hypothesis was that performance on the dependent variables would not differ significantly due to the type of light, the beam width combination, or to an interaction effect. The dependent variables were thruster air consumption, elapsed time, translational error frequency, and error recovery time for approach and docking, and Z and pitch axes alignment at docking.

Three studies conducted at MSFC were the only sources of background information available on the topic of teleoperator lighting. In an initial TMS lighting study, Shields and Henderson (1981) found that on-board floodlighting was effective for close proximity illumination of target features. A study conducted under simulated solar illumination indicated that camera line-of-sight, target alignment, and target illumination interacted to affect operator performance (Shields, Piccione, Kirkpatrick, & Malone, 1982). Based on the recommendations of Test Report No. 03-85-OMV-01, <u>OMV Approach and Docking with Onboard Flood or Spot Lights</u>, both flood and spotlights were chosen for investigation in this test.

Three women and two men were chosen from the subject pool to participate in the lighting test. Three of the subjects had participated in previous tests. The other two subjects completed the standard training series, and they practiced the approach and docking task until their performance stabilized.

General Electric (GE), sealed-beam lamps were chosen for use in the lighting evaluation. These bulbs were the closest commercial equivalents to flight-qualified lighting available. The floodlight beam widths were 80 x 20 degrees and 40 x 7 degrees, and the spotlight beam widths were 5 x 5 degrees and 10 x 4 degrees. These bulbs were installed in the capture device light fixtures as required by the experimental condition under investigation. The lights were pointed to follow the camera line-of-sight as closely as possible.

The effects of flood and spotlight beam width were tested in a 2 x 4 x 5 (type of light x beam width combination x subjects) factorial design. Each of the subjects attempted the approach and docking task three times under the eight conditions shown in Table 3.1.

TABLE 3.1

TEST NO. 06-85-OMV-03-A EXPERIMENTAL DESIGN

	Type of Light and Beam Widths	
Camera Location	Floodlight	Spotlight
Bore Sight	80 x 20	10 x 4
Perimeter	80 x 20	10 x 4
Bore Sight	40 x 7	5 x 5
Perimeter	40 x 7	5 x 5
Bore Sight	80 x 20	10 x 4
Perimeter	40 x 7	5 x 5
Bore Sight	40 x 7	5 x 5
Perimeter	80 x 20	10 x 4

Two test conditions (one floodlight and one spotlight condition) were alternately presented in four test sessions with each subject. The order of presentation was counterbalanced within and between subjects. Test runs began with the TOM-B aligned with the target. The Z axis was offset +20cm and the pitch axis was offset +5 degrees at the beginning of each run. The on-board lights provided the only illumination in the flat floor facility.

A 2 x 4 x 5 (type of light x beam width combination x subjects) ANOVA was applied to the data collected during the lighting test. Significant differences due to the type of lights (flood or spotlights) were found in thruster air consumption for approach ($F(1,4) = 8.34$, $p < .05$), elapsed time for docking ($F(1,4) = 15.35$, $p < .05$), translational error frequency during docking ($F(1,4) = 36.19$, $p < .05$), and error recovery time during docking ($F(1,4) = 15.87$, $p < .05$). Performance on each of these dependent variables was degraded by the spotlight conditions in comparison to the floodlight conditions. Thruster air consumption for docking tended to be lower under the floodlight conditions than under the spotlight conditions, $F(1,4) = 6.21$, $p < .10$. A statistical trend also occurred in translational error frequency during approach due to an interaction effect of type of light and beam width, $F(3,12) = 2.74$, $p < .10$. This difference was due to increased numbers of errors in the 40 x 7 bore sight plus 80 x 20 perimeter floodlight condition and in the 5 x 5 degree bore sight plus 5 x 5 degree perimeter spotlight condition. Alignment of the Z axis tended to be further from ideal when two 80 x 20 degree floodlights or two 5 x 5 degree spotlights were used, $F(3,12) = 2.70$, $p < .10$.

Results of the lighting requirements test supported previous findings which indicated that floodlighting improved performance during docking. The results for approach operations were less definitive. Thruster air consumption during approach increased when spotlights were used. The frequency of approach translational errors tended to increase when two 5 x 5 degree spotlights or a 40 x 7 (bore sight) and 80 x 20 (perimeter) floodlight combination were employed. Alignment of the Z axis tended to be farthest from ideal when two 5 x 5 degree spotlights or two 80 x 20 degree floodlights were used. No other differences occurred during approach operations. Based on the test results, the findings of previous research, and subject comments during debriefing, it was recommended that an 80 x 20 degree, bore-sighted floodlight with either a 40 x 7 degree perimeter floodlight or a 10 x 4 degree spotlight be further investigated.

4.4 OMV Vision Systems: Field-of-View and Light Intensity

Test Report No. 10-85-OMV-04-A

The objectives of this investigation were to review the research on camera field-of-view (FOV) for the performance of remote operations and to conduct an empirical evaluation of the effects of the intensity of the on-board OMV lights on the quality of the remote visual image. A literature search was conducted on the topics of FOV in military flight operations and teleoperator FOV research.

A series of studies conducted between 1968 and 1972 investigated the effects of camera FOV and other aspects of cockpit visual systems on pilot performance of target acquisition tasks. These three studies were conducted using a flight simulator with experienced military pilots serving as subjects. The simulator consisted of a terrain model with three axes of motion and a gimble mounted camera with three axes of motion. The simulated flights began at a range from the target of 45,000 ft, and the subject's task was to detect and acquire the target as quickly as possible.

The first study in this series concerned the effects of FOV, target to background contrast, and target briefing on detection and recognition (Ozkaptan, Ohmart, Bergert, & McGee, 1968). FOVs of 4.9, 7.3, 9.7, and 14.5 degrees were investigated. FOV did not affect detection or recognition when the subjects were briefed on the target area before the test. When the subjects were not briefed on the target area, the probability of detection decreased as FOV increased. Slant range to the target increased as target to background contrast increased and FOV decreased. The results of the study indicated that a narrow FOV improved performance when subjects were not briefed on the target area and when high contrast targets were used.

In the same series, Bergert and Fowler (1970) investigated the effects of 7.3 and 14.5 degree FOVs, target to background contrast, type of background and static or dynamic flight modes on target acquisition. Larger visual angles were required for detection and recognition with the 7.3 degree FOV, however significantly fewer targets were missed than when the 14.5 degree FOV was used. Recognition in the dynamic flight mode was most difficult when the 14.5 degree FOV was used. Again, the narrower FOV was most effective for detection and recognition of high contrast targets.

The third test in the series (Fowler & Jones, 1972) studied the effect of FOV on a pilot's ability to detect and recognize a TV displayed target after it had been detected visually through the cockpit canopy. FOVs of 4.8, 9.6, and 14.5 degrees were employed as the simulator approached prebriefed target areas. The time required for TV detection was significantly lower and range to the target was significantly longer for the 4.8 degree FOV than for the 9.6 and 14.5 degree FOVs.

Grant, Meirick, Polhemus, Spencer, Swain, and Tewell (1973) evaluated visual systems for the design of the Free Flying Teleoperator through manipulator and motion base simulations. The authors recommended a hybrid stereo-monoscopic system with a 9 to 54 degree FOV, and stated that the ability to reduce the FOV (zoom) increased both stereo and monoscopic acuity in distance viewing.

FOV was not specifically tested in the verification test series; however, some observations on the topic were made. An equipment change resulted in a reduction the the perimeter camera FOV from 44.8 to 22.4 degrees between Tests No. 04-85-OMV-02 and 06-85-OMV-03-A. Four subjects participated in both these tests, and their remarks during debriefing indicated that the wider FOV was preferable for the perimeter camera. The results of OMV Vision Systems: Operator Control of Zoom, Focus, and Iris (Test Report No. 10-85-OMV-04-B) indicated that a variable FOV may be advantageous for the OMV perimeter camera.

Based on available information, it was recommended that a variable FOV in a range around 4 to 55 degrees be considered for the OMV perimeter camera and that the FOV be placed under operator control. The width of a set FOV on one camera and the type of control feedback were cited as issues requiring further study.

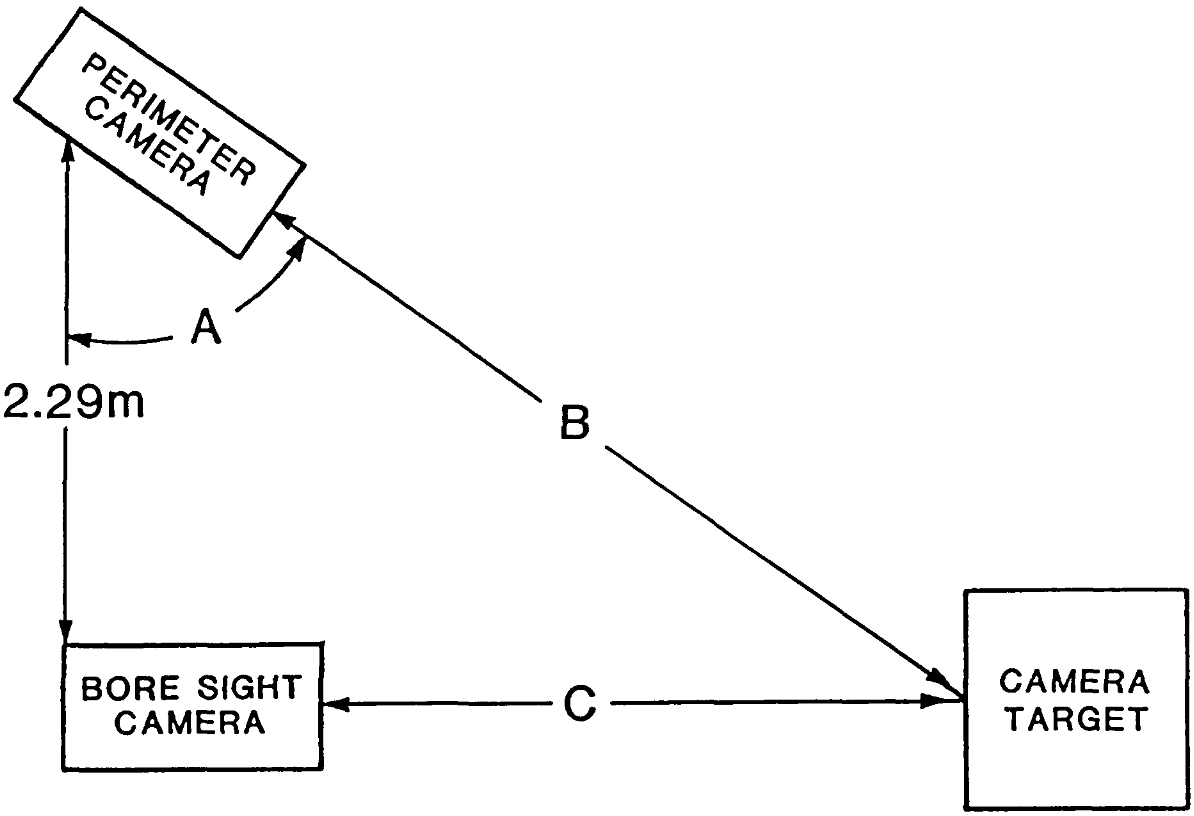
The light intensity evaluation was preceded by a review of the human factors research on the effects of monitor luminance and ambient lighting on operator performance. Six sources of information on this topic were reviewed and no consensus of recommended luminance or illumination was found. The range of suggested video luminance was 30 to 170 cd/m^2 and recommended ambient illumination ranged from 100 to 750lux.

Based on the recommendations of Test Report No. 06-85-OMV-03-A, an 80 x 20 degree floodlight at the bore sight camera location with either a 40 x 7 degree floodlight or a 10 x 4 degree spotlight located with the pan and tilt perimeter camera were chosen for investigation. The HST mock-up was chosen as the target for this evaluation, and the RMS camera target in the center of the mock-up was used as the reference point for light/camera alignment throughout the investigation.

The effect of light intensity on the remote monitor image was evaluated by moving the TOM-B through a typical approach and docking scenario under dark-side conditions while varying the intensity of both beam width combinations. The approach/docking scenario is illustrated in Figure 3.7. Light intensity was varied by voltage inputs from 5 to 12 VDC (± .05 VDC). Intensity at the RMS camera target, the bore sight and perimeter camera lenses, and the luminance of both camera monitors were measured at each approach/docking position with a digital photometer. The monitor images were also evaluated by test personnel for clarity and for excessive or insufficient target illumination.

The 80 x 20 and 40 x 7 degree floodlights produced a range of 159 to 560 cd/m^2 of bore sight monitor luminance and a range of 67 to 441 cd/m^2 on the perimeter monitor. The 80 x 20 degree floodlight combined with the 10 x 4 degree spotlight produced luminance ranging from 165 to 643 cd/m^2 on the bore sight monitor and 76 to 502 cd/m^2 on the perimeter monitor. The acceptable range of video luminance for both monitors (95 to 350 cd/m^2) was higher than the range recommended by previous research.

The evaluation revealed several factors which were cited as requiring consideration in evaluations of the visual system chosen for flight. The position of the simulator in relationship to the target was one of the main factors affecting monitor luminance in the study. The distance to the target as well as camera/light/target geometries should be considered in future evaluations. The nature of the target surface (reflective or nonreflective) was also cited as requiring consideration. It was further suggested that a single intensity setting might not meet illumination requirements in all OMV missions and that a system which allowed light intensity to be varied by the operator or other personnel should be investigated.



Position	Dimension A	Dimension B	Dimension C
Maximum distance to target	84 deg.	21.4m	21.3m
50 percent of distance to target	80 deg.	10.9m	10.7m
75 percent of distance to target	67 deg.	5.7m	5.3m
Docked with target	24 deg.	2.5m	1.0m

Figure 3.7: Camera/Target Geometries of Four Positions in a Typical Approach and Docking Scenario

4.5 OMV Vision Systems: Operator Control of Zoom, Focus, and Iris

Test Report No. 10-85-OMV-04-B

This test was conducted to examine the effect on task performance of placing the iris of the bore sight camera and the iris, zoom, and focus of the perimeter camera under operator control. The null hypothesis was that performance on the dependent variables (thruster air consumption, elapsed time, translational error frequency, and error recovery time for approach and docking, and alignment of the Z and pitch axes at docking) would not differ significantly due to the addition of the camera lens controls to the approach and docking task.

The OMV Requirements Document (1985) specified that one of the OMV cameras would be equipped with pan, tilt, and zoom functions. A search of the NASA Technical Library revealed that no studies specifically concerning operator control of zoom, focus, and iris functions during teleoperation were available. In a study to gather baseline data on teleoperator lighting for solar illumination conditions, Shields and Henderson (1981) recorded remote monitor images in order to evaluate the effects of target illumination on the visual image presented to the operator. They found that when an automatic camera iris was used, intense light reflected off the target caused the image to be overly bright, and critical target features were obscured. This image "blooming" resulted because the automatic iris utilized average scene lighting to determine the iris setting. The result of averaging a black background and a highly reflective target was that too much light entered the lens, causing the image to be overly bright. This same auto iris effect was noted in Test No. 03-85-OMV-01 of the TOREF verification test series. Both of these studies recommended that placing the iris under operator control should be investigated.

Three men and two women were selected from the subject pool for this test. Four of the subjects had participated in previous tests. The new subject was trained according to standard procedures and practiced the approach and docking task under dark side conditions until performance stabilized.

The TOM-B perimeter and bore sight cameras were equipped with Canon motorized lenses. The bore sight FOV was set at 24 degrees and the perimeter FOV was variable from 4 to 24 degrees. An 80 x 20 degree floodlight was located with the bore sight camera, and a 10 x 4 degree spotlight was located with the pan and tilt perimeter camera. Selection of these lights was based on the results of the lighting evaluation previously described, and light intensity was set to produce optimal monitor luminance in accordance with the results of that evaluation. The iris of the bore sight camera and zoom, focus, and iris of the perimeter camera were controlled by the subjects using four toggle switches located on the left RWS auxiliary control panel (Figure 1.5).

The subjects made five test runs under three camera lens adjustment conditions. In the baseline condition, the camera lenses were set to provide optimal visual cues, and no adjustments by the subject were required. The second, or minimal condition, required the subject to adjust the irises of both cameras as soon as they had placed the TOM-B in motion. The moderate adjustment condition required the subject to manipulate the irises of both cameras and the zoom and focus of the perimeter camera throughout the task in order to optimize visual cues. The lens controls were set at positions which were not optimal at the beginning of each run in the minimal and moderate conditions. Lens settings were determined using a random numbers table.

The data were analyzed using one-way ANOVAs with three repeated measures on one factor. With the exception of thruster air consumption for docking, the null hypothesis that added camera controls would have no significant effect on performance failed to be rejected for all dependent variables. Thruster air consumption during docking was significantly greater in the minimal and moderate conditions than in the baseline condition, $F(2,8) = 6.91$, $p < .05$. Thruster air consumption for approach tended to decrease as the frequency of camera adjustments increased, $F(2,8) = 3.95$, $p < .10$. Approach thruster air consumption was lowest in the moderate condition and highest in the baseline condition. A trend occurred for elapsed time during approach to be higher in the baseline condition than in the minimal and moderate conditions, $F(2,8) = 4.39$, $p < .10$. Error recovery time during docking tended to be lower under the baseline condition than under the minimal and moderate conditions, $F(2,8) = 3.93$, $p < .10$. A trend was evident for alignment of the pitch axis to be closest to the ideal in the baseline condition, $F(2,8) = 3.80$, $p < .10$.

After testing was concluded, a post-test observation was conducted. This post-test series was conducted in the same manner as the test runs except that the subjects began the runs with optimal visual cues and used the camera lens controls at their discretion in order to optimize the remote image throughout the run. During the test runs and the post-test observation, video recordings were made of the subjects' use of the camera controls. These recordings were analyzed in order to describe the subjects' control behaviors. The subjects made only slightly fewer adjustments in the post-test observation, when they were allowed to make adjustments as they chose, than they did in the moderate test condition when they were forced to adjust the lenses. Under both conditions, the frequency of adjustments made was approximately four times higher during approach than during docking.

Based on the results of the test, it was concluded that adding control of the camera irises and perimeter camera zoom and focus control to the OMV operator's task would not degrade total task performance and that performance of approach operations would be enhanced. Subjects' video recorded control behaviors and their comments during debriefing indicated that the ability to zoom the perimeter camera and to control both camera irises would be advantageous to the OMV operator. It was recommended that this issue be further investigated along with all tasks required of the operator and in conjunction with reduced video transmission bandwidth. It was also recommended that iris control be investigated under solar illumination conditions.

4.6 OMV Operation with Reduced Video Frame Rate

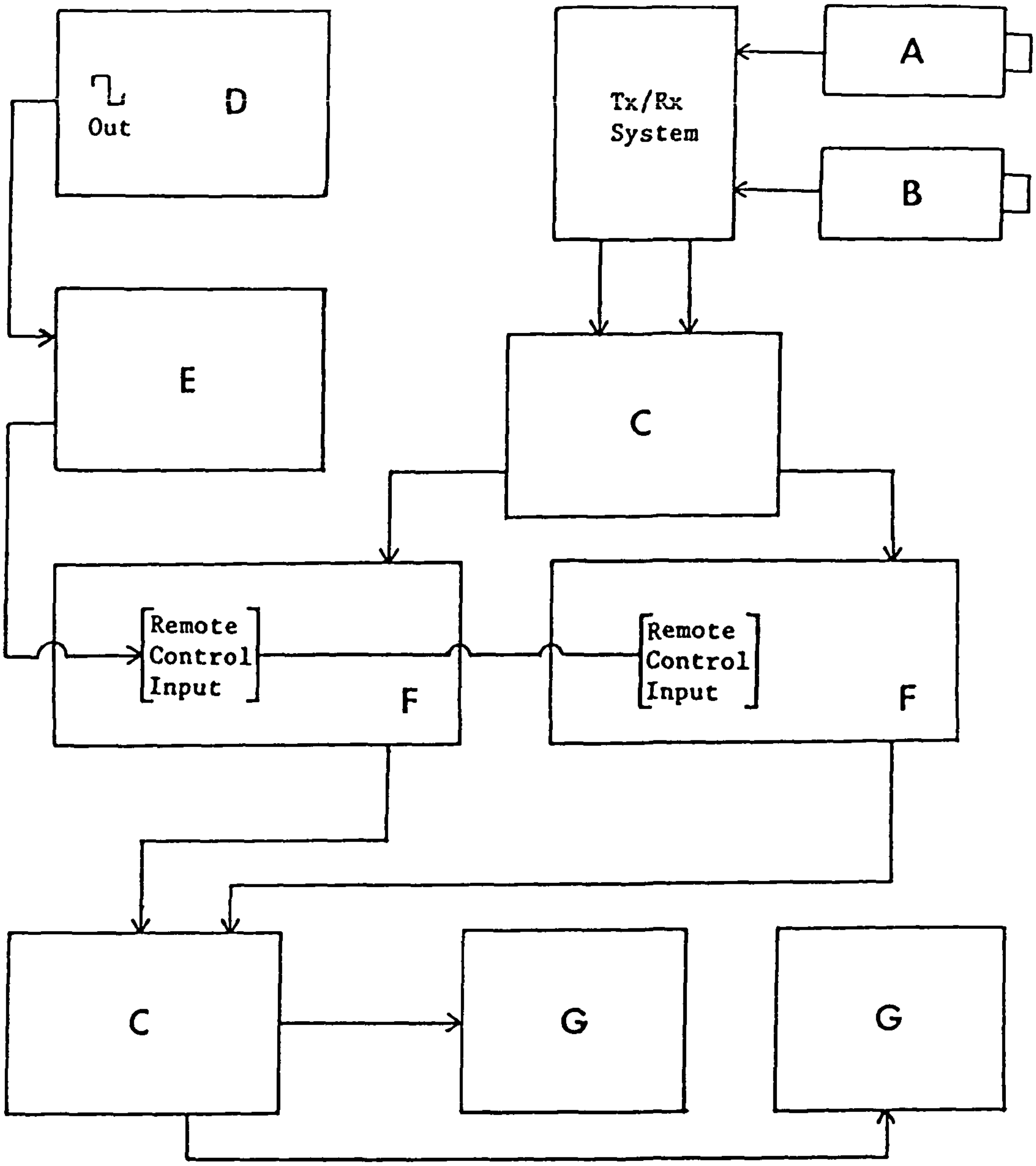
Test Report No. 11-85-OMV-05

The objective of this test was to investigate the effects of reducing the frame rate of the video image presented to the OMV operator. The null hypothesis was that performance of the approach and docking task would not be significantly affected by frame rates of 30, 15, 10, 5, 3, 1, 0.5, and 0.1 frames/second (fr/s).

The possibility of drastically reducing the the video transmission bandwidth from the OMV to the ground control station has been foreseen for OMV operations. The video bandwidth required for transmission is a function of frame rate, gray scale, and resolution. A reduction in one or more of these parameters may result in a substantial reduction in the required bandwidth. Ranadive (1979) investigated bandwidth reduction for undersea teleoperation. After varying frame rate, gray scale, and resolution for the performance of two remote manipulator tasks by two subjects, Ranadive concluded that performance was not degraded when frame rate was reduced to 3 fr/s, or when resolution was reduced to 64 x 64 pixels/frame, or when a gray scale of 1 bit of gray/pixel was employed. Studies of reduced video bandwidth were conducted during the Remotely Piloted Vehicle (RPV) program. The proposed RPV was a remote assault vehicle, and three studies were conducted using an RPV simulator. At the conclusion of this series of studies, the researchers recommended that a bandwidth compression system which provided 3.75 fr/s, 256 x 256 pixels/frame of resolution, and 1 bit of gray/pixel be implemented in the RPV design. Systems analysis simulations, which evaluated 10 bandwidth compression systems, confirmed this recommendation (Hershberger & Vanderkolk, 1976). In summary, the previous research indicated that a frame rate as low as 3 fr/s would not significantly degrade the performance of remote tasks.

The frame rates employed in this test were 30, 15, 10, 5, 3, 1.5, 0.5, and 0.1 fr/s. These rates were chosen in order to cover the widest range of rates which could conceivably be applicable to the OMV visual system design. Two women and three men served as subjects in the test; all subjects had participated in previous TOREF tests.

The TOM-B was equipped with an 80 x 20 degree floodlight at the bore sight camera location and a 10 x 4 degree spotlight at the pan and tilt perimeter camera location. Two Tektronix synchronizers, driven by a wave form generator and a pulse generator, were used to store and display inputs from the TOM-B cameras at the selected rates. This system, which allowed continuous selection of frame rates from 0.01 through 30 fr/s, is shown in Figure 3.8.



Component Specifications	
A	XES Color Camera (TOM-B Perimeter Camera)
B	Panasonic Color Camera, WV-3890-B (TOM-B Bore Sight Camera)
C	American Data Distribution Amplifier
D	Krohn-Hite Wave Form Generator, model 5400A
E	EH Research Labs Pulse Generator, model 710
F	Tektronix 110-S Synchronizers, model LR37158
G	Mitsubishi Color Monitors, model AM-1301

Figure 3.8: Video System Used to Produce Reduced Frame Rate

Each subject attempted the approach and docking task five times under the eight frame rate conditions. The test was conducted under dark-side conditions, and the frame rate conditions were randomly presented to the subjects. In order to avoid introducing an uncontrollable source of variation into the test results, camera zoom, focus, and iris controls were not used during the test

One-way ANOVAs with repeated measures on one factor were employed to test for significant differences in run success, total thruster air consumption, elapsed time, frequency of translational errors, error recovery time, and Z and pitch alignment. Run success was significantly degraded by frame rates of 0.5 and 0.1 fr/s, $F(7,28) = 43.62$, $p < .001$, but was not affected by rates of 1 fr/s and above. Only one successful dock occurred in the 0.1 fr/s condition; therefore, data from this condition were excluded from further analysis. Total elapsed time was significantly higher in the 1 and 0.5 fr/s conditions than in the 30, 15, 10, and 5 fr/s conditions, and the 3, 1, and 0.5 fr/s rates resulted in significantly higher total times than did the 15 and 10 fr/s rates, $F(6,24) = 3.12$, $p < .025$. The effects of zone of operation and reduced frame rate were analyzed using 2 x 7 x 5 (zone of operation x frame rate x subjects) ANOVAs. The time required for docking was significantly higher when the frame rate was 1 and 0.5 fr/s than when the rate was 30, 15, 10, or 5 fr/s, $F(6,24) = 3.12$, $p < .025$. The analysis revealed no difference in the remaining dependent variables due to the frame rate conditions. Although some trends were evident, no conclusions could be drawn due to the variability of the data.

The test results demonstrated that the frame rate of the OMV visual system could be reduced to at least 5 fr/s without affecting operator performance if the resolution and gray scale were not degraded below normal levels. The 5 fr/s level was slightly higher than the 3.75 fr/s rate which repeatedly appeared in previous research as the threshold for performance degradation. It was concluded that this difference in research findings was due to differences in equipment capabilities between the present and past studies. Rates between 7.5 and 3.75 fr/s were not available for investigation in previous research. This difference indicated that a range of frame rates between 5 and 3 fr/s should be subject to further investigation. It was also recommended that reduced frame rate be investigated in conjunction with optical zoom, command time delay, and degraded resolution and gray scale.

4.7 The Utility of Stereo Vision for Remote Operations: A Review

The purpose of this review was to develop an annotated bibliography, examine research findings, gather information available on the topic of stereo vision, and define the relative advantages and disadvantages for use with the OMV. The annotated bibliography appears in the reference section of this report (Section 6.4). A literature search was conducted from the NASA Technical Library utilizing the NASA RECON System to gather information on stereo vision. Additional information was obtained from the Essex Corporation in-house library.

The perception of depth will be important for successful docking, target acquisition, manipulation, servicing, repair, refurbishment, and similar activities in support of space operations required of the OMV. Depth perception from a two-dimensional (2-D) image is obtained as an observer extracts available monocular and coding cues relative to the depths of displayed objects. Three-dimensional (3-D) depth perception, or stereopsis, results from binocular disparity, when each eye views a scene from a slightly different vantage point with the images fused together.

Three-dimensional video systems for teleoperation utilize stereo-pair displays in which a pair of images containing lateral or binocular disparity appropriate for the relative depth of the objects is presented. Stereopsis is produced through the utilization of mirrors, prisms, cross-polarized glasses, red and green filter glasses, lenticular screens, and alternating shutter glasses. The two most commonly used stereo display systems referred to in the current research are illustrated in Figures 3.9 and 3.10.

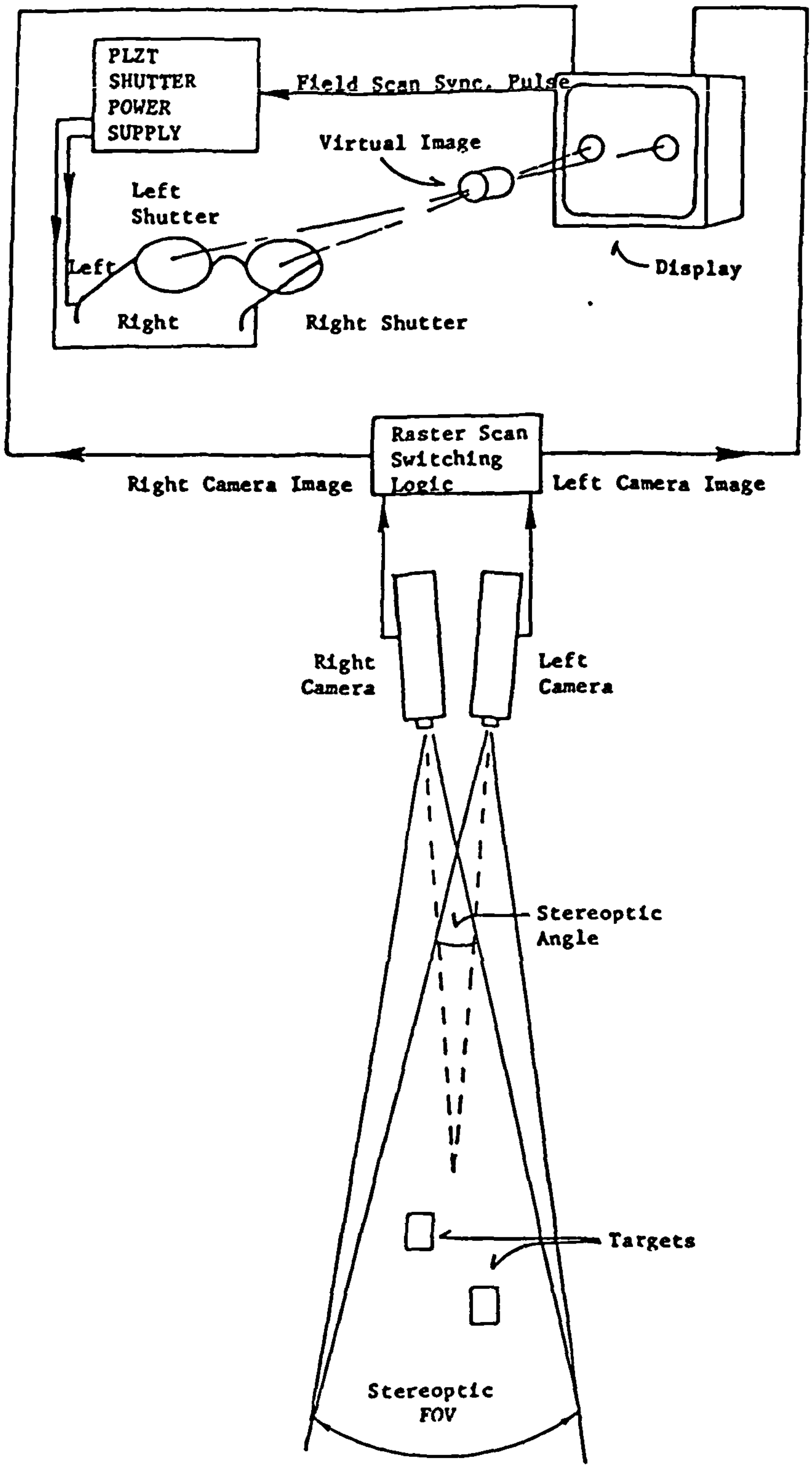


Figure 3.9: Piezioelectric Lathanum Lead Zirconate Titanate Stereo Display System

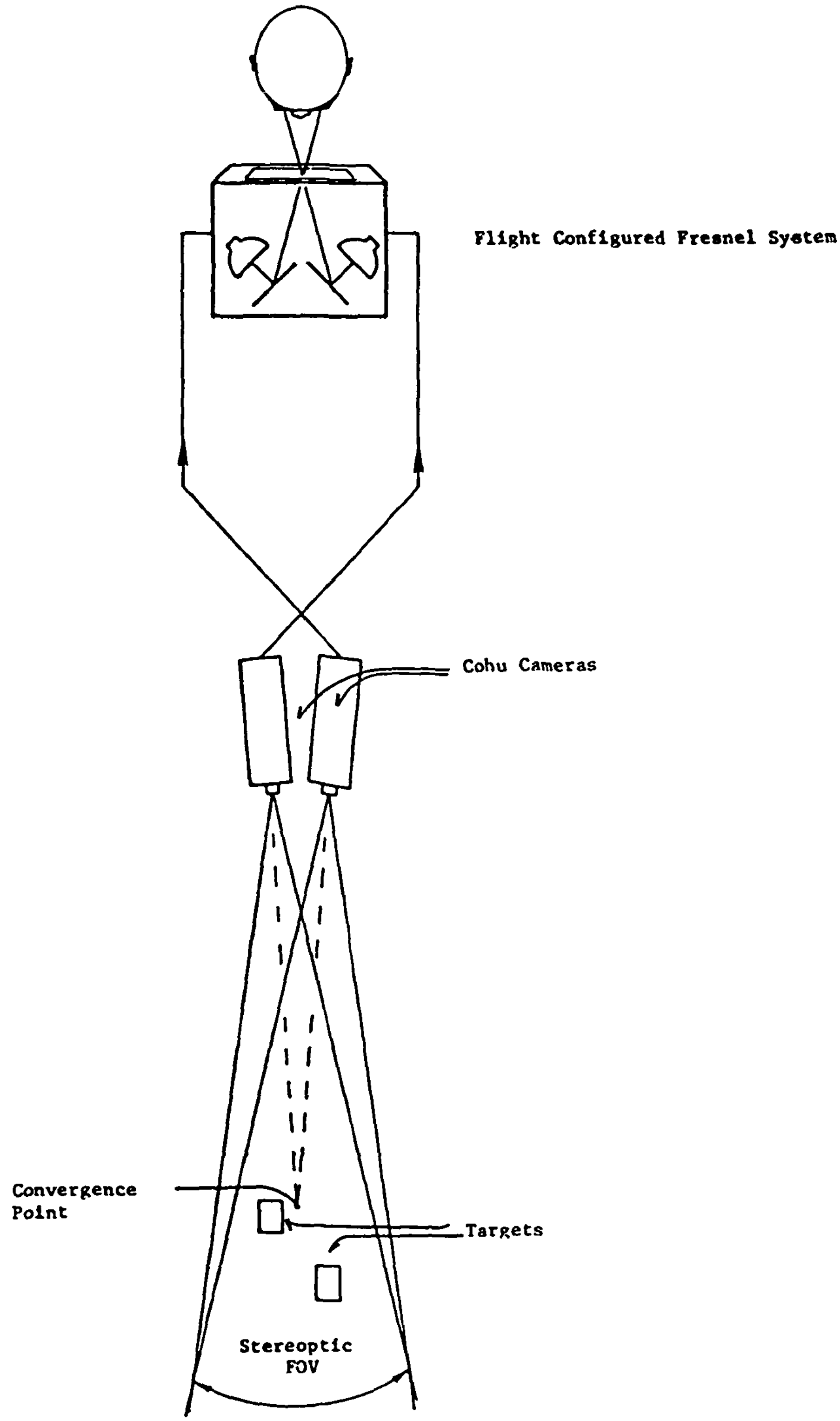


Figure 3.10: Flight Configured Fresnel Stereo Display System

Most research in the area of stereo display systems compares task performance using a stereo system with performance using a mono display system. The results of the studies cited in the reviewed literature varied greatly, with evidence supporting performance advantages for both display systems. However, one finding consistently occurred throughout the studies reviewed: that a mono display system with two orthogonal views produced similar, if not significantly better, task performance than a stereo display system. The research findings are presented below in three categories: those who found performance advantages using a one-view mono system, a stereo system, or a two-view mono system.

Performance Advantage Using a One-View Mono System

Fredrick, Shields, & Kirkpatrick (1977)

Examining the accuracy of operator range estimation using a Fresnel TV system with a 3-D cursor and two mono systems with a fixed and moveable ranging cursor, the authors found that the stereo system produced a higher overall error percentage than either of the two monoptic systems. In addition, performance using the stereo system required triple the performance task time of the mono system.

Performance Advantage Using a Stereo System

Merritt (1982)

The author suggested that the absence of hard data supporting the use of stereo systems was due to the poor quality of the stereo systems evaluated in comparisons with mono systems and that in most experiments the stereo system was inadequately set up. Two studies were cited to illustrate this point. Kama and DuMars (1964) found no difference in performance of a peg-in-hole remote manipulator task when either a stereo or mono system was employed. In a replication of the task using direct rather than TV viewing, Chubb (1964) found stereo vision to be significantly better than mono vision. The author stated that the significant difference resulted from eliminating the confounding variable of display resolution inequality. Although the author assumed direct viewing was an appropriate method for eliminating the inequality of display resolution between stereo and mono systems, he failed to recognize that direct viewing and display viewing cannot be equated. Comparing a commonly viewed mono display system with one-eyed vision, which is an unnatural way of viewing for most individuals, is absurd.

Pepper, Cole, Merritt, & Smith (1978)

Performance on the Howard-Dolman Two-Rod Depth Discrimination test, performance of a depth perception task using Julesz' dot patterns, and performance of a remote manipulator task were enhanced when a stereo display system was employed as opposed to a mono system. In addition, direct viewing produced better performance than the two stereo systems used in the tests.

Shields, Kirkpatrick, Fredrick, & Malone (1975)

In the first of two studies comparing stereo and mono displays, the operators' ability to position a variable target at the same range as a fixed target was evaluated. Results indicated absolute errors for the mono system were three times that of the stereo system. In a similar study with varied video system parameters, the authors found that performance was equal for both display systems when an angle between the camera viewing axis and motor axis existed. It was concluded that the angle caused target separation to become a lateral dimension on the display. Therefore as the viewing angle decreased, the reliance on stereo display increased.

Smith, Cole, Merritt, & Pepper (1979)

An evaluation of operators' ability to complete remote manipulation tasks was compared using a PLZT stereo viewer and a mono display system under three visibility conditions. With experienced operators as subjects, performance was significantly better when the PLZT viewer was employed. With inexperienced operators, no significant differences were found. The authors stated that stereo performance produced more errors under all visibility conditions. In a task in which 1/2 inch rope was threaded through two hoops, performance was best when the stereo display was employed, and the stereo system provided a significant advantage over the mono display as visibility and task objects become more complex.

Performance Advantage Using a Two-View Mono Display System

Freedman, Crooks, & Coan (1977)

Several alternative video systems were evaluated in terms of four remote manipulation tasks. The video systems were a black and white mono system, a color mono system, a two-view mono black and white system, and a black and white stereo system. The authors concluded that for a combination of remote operations, the two-view mono system had a performance advantage over the other display systems.

Huggins, Malone, & Shields (1972)

The ability to judge depth and estimate distances between two offset targets using stereo and mono display systems was examined in this study. The best distance estimation performance was obtained with two mono cameras located orthogonal to each other in a horizontal plane. Performance with a one-view mono system improved when the camera was positioned above the work surface. The authors also found that the stereo TV system yielded no better performance than the one-view mono system regardless of the position of the monoscopic camera.

Tewell, Ray, Meirick, & Polhemus (1974)

Three evaluations comparing stereo and mono TV systems were conducted. The authors concluded that the stereo permits adequate alignment of objects regardless of the difference in viewing angles and object size and shape. For remote manipulator tasks, the mono system with two orthogonal views was approximately equal to the stereo system in terms of performance. The authors recommended the Fresnel stereo display system for teleoperation. Conclusions based on this research should be made with caution since no inferential statistics were reported. Additionally, due to the fact that the Fresnel stereo system was developed by Martin Marietta Corporation, their recommendation of this system for teleoperation could be biased.

Most of the research recommending a stereo display system over a mono system resulted from comparisons with a one camera mono system. Due to the fact that the OMV Requirements Document (1985) specified that a minimum of two TV cameras would be required for the OMV, the results from research comparing stereo systems with one camera mono systems were not applicable in making recommendations for the OMV. However, recommendations can be made for the OMV based on the results and conclusions from research comparing stereo displays and mono systems with two orthogonal views. All research comparing these systems indicated that the two systems were approximately equal with respect to their effects on operator performance. To determine whether a stereo system should be recommended for use with the OMV, the advantages and disadvantages relative to those of a two-view mono system should be examined.

Stereo system advantages include the continued presentation of three-dimensional scenes regardless of camera location and a resistance to image degradation by poor visibility conditions. The disadvantages of stereo systems are increased eye fatigue, which is compounded by viewing of auxiliary displays and controls, the additional maintenance of the display system, and increased system cost for the display, calibration, and sequencing of the sensors. Currently, the only flight-qualified stereo display system requires two cameras and produces two signals. If the stereo system is the only display system implemented in the OMV design, the bandwidth required would be equal to that of a mono system with two orthogonal views. However, if the stereo system is used in conjunction with another video system, the bandwidth required would be significantly increased. A greater bandwidth requirement presents a problem since a reduction in video bandwidth has been proposed for OMV operation. One bandwidth reduction technique, which is under investigation, is reducing the video frame rate. The effects of reduced frame rate on a stereo display system have not been evaluated. Reducing the frame rate of stereo transmissions may cause greater eye fatigue induced by the flicker associated with slower frame rates and may eliminate stereopsis due to the alternating visual images presented through the stereo display.

Further research on the effects of reduced bandwidth on stereo display systems is necessary before a stereo system is considered for implementation in the OMV visual system. Based on the information currently available, a two-view mono system is the most appropriate visual system for the OMV.

4.8 The Reconfigurable Workstation, Short Task Comparative Analysis

Test Report No. 11-84-RWS-01

This test was conducted to compare the RWS with a workstation design used in previous teleoperator research and to gather baseline data for the OMV Ground Control Station Guidelines. The null hypotheses were that task performance and subject reports of discomfort would not differ significantly due to the two workstations.

The TOREF required a workstation which combined multiple monitors, a keyboard, and two 3DOF hand controllers for remote docking analyses. The RWS was designed by Essex Corporation to meet these requirements while incorporating the most current human factors guidelines on workstation design. A review of the workstation design research revealed that workstations which incorporated adjustable worksurfaces, keyboards, monitors, and chairs reduced operator fatigue and improved performance. A summary of this review appears as an annotated bibliography in Section 6.5.

Six women and six men participated in the study. The subjects were free of visual and motor impairment and were representative of the subjects who participated in succeeding TOREF tests.

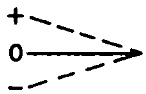
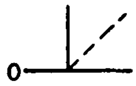
The RWS (Figure 1.3) was designed with a primary worksurface which was adjustable from +8 to -6 degrees and supported the operator's forearms during hand controller operation. The keyboard support panel was located in the middle of the primary worksurface and was adjustable from +5 to +22 degrees above the worksurface. The primary monitor panel could be adjusted from 90 to 110 degrees. Task performance on the RWS was compared with performance on a standard workstation. The standard workstation was based on a configuration used in the previous teleoperator laboratory, and its dimensions conformed to human factors design guidelines. Both workstations contained a 33cm Mitsubishi color monitor, an RCA Data Terminal, low-profile keyboard, a Kraft Systems Incorporated hand controller and an Emcor chair. A computer-generated typing and tracking task were performed on both workstations. The typing task required the subject to input 100 three to six letter words after they were prompted on the monitor. The tracking task generated 100 random cursor/target positions on the monitor. The subject's task was to move the cursor to the target and acquire it by pressing a button on the hand controller. Both tasks were computer scored. The dependent variables for the typing task were the time required to input each word and the number of correct letters. The tracking task dependent variables were the percentage of targets acquired and the average time per target.

Each subject performed both tasks on each workstation in sessions which were separated by at least one week. The subjects were randomly assigned to groups with respect to order of treatment condition (workstation) and task order (typing and tracking). The tasks were explained and demonstrated to the subjects by the test conductor. For the RWS trials, the workstation adjustments were demonstrated and the subjects were encouraged to adjust the workstation to provide maximum comfort. The RWS positions chosen by each subject were recorded. After task completion on each workstation, the subjects completed a comfort questionnaire which was based on work by previous researchers.

One-way ANOVAs with repeated measures were used to analyze task performance. No significant differences were found due to the workstation used. Performance was also analyzed for differences due to sex and a sex/workstation interaction. Again, no differences in performance were evident. The only difference in subject discomfort was that eight subjects reported increased tension in their wrists when operating on the standard workstation. The positions of the RWS chosen by the subjects are shown in Table 3.2.

TABLE 3.2

POSITIONS OF THE RWS (DEGREES) CHOSEN BY TWELVE SUBJECTS

	RWS Worksurface		
	Primary Worksurface	Keyboard	Primary Visual Display
Subject			
1	-4	14	100
2	+4	22	97
3	-6	14	90
4	+2	21	97
5	-3	9	102
6	+6	6	104
7	-4	13	99
8	-2	18	110
9	+1	14	98
10	-5	8	104
11	-5	5	93
12	-2	16	99
Range	-6 to +6	5 to 22	90 to 110
Median	-2.5	14	99

The null hypothesis that performance would not differ according to the workstation failed to be rejected. It was suggested that the short task duration (approximately 20 minutes) was not sufficient to induce subject fatigue. Because the RWS was designed for long-term operations, no difference occurred in the performance of the short duration task. It was noted that the reported increase in wrist tension might prove to be significant during the performance of longer tasks, and it was recommended that the RWS be further evaluated for the performance of realistic teleoperator tasks with an eight-hour work shift duration. It was noted that the full range of RWS adjustments were utilized by the subjects, indicating that the adjustments should be included in control station design because they would be advantageous, especially for populations of operators with diverse body sizes.

4.9 Ground Control Station Design Guidelines

The workstation design guidelines presented in this section are based on the remote workstation requirements of the MSFC/TOREF, and as such, the findings and recommendations are limited to similar applications. This does not preclude extending the findings to general workstation issues, but validating the applicability is the responsibility of the user organization.

The design guidelines address the human engineering issues associated with the remote control of and feedback from teleoperated tasks. They are the result of findings and observations concerning operator behavior in approach and docking studies conducted at the TOREF from September 1984 through December 1985. The workstation used in the evaluations, the RWS, was designed specifically for remote operations in the TOREF. The purpose of the RWS was to accommodate the hardware required for remote operations involving multiscreen displays, keyboards, and flight hand controllers. The workstation was designed to accommodate a wide range of human operators and to be physically and functionally reconfigurable. The RWS has been described in detail in Analysis and Selection of a Remote Docking Simulation Visual Display System, Contract NAS8-35636 Final Report No. H-84-04.

Based on the tasks conducted in the TOREF over the past two years, the following workstation design guidelines were developed to support the design and integration of the OMV ground control console.

Operators

During the operating lifetime of the OMV, a wide range of candidate pilots and payload specialists will be involved in the program. For this reason, anthropometric data for the smallest to the largest potential operator should be used as the design basis for the Ground Control Console (GCC). The Space Station program is working with the range encompassing the 5th percentile oriental female through the 95th percentile Air Force male. The specificity of the oriental female is not given, but current recommendations are to use the 5th percentile Vietnamese female anthropometry based on the regression equations cited in the Anthropometric Source Book Volume 1, NASA Reference Publication No. 1024 (1978).

The RWS was not designed with data from the 5th percentile oriental female but was based on 5th percentile U.S. female data. Modifications may be necessary in some aspects of the control and display layout to accommodate the 5th percentile oriental female and the 95th percentile U.S. male. This is an issue requiring further design analyses.

Normal visual acuity and hand-eye coordination are anticipated requirements for remote operators. Color discrimination should be normal, considering the potential applications of polychromatic displays.

Training will be the most significant variable which an operator will bring to the GCC, and it is recognized that training in mission simulations should be conducted at an operational replica of the GCC. This will have a positive effect on the transfer of skills and knowledge from the simulations environment to the operational one. This can be accomplished by training in the Mission Operations Center during non-operational periods or by having a dedicated training facility.

Primary Visual Displays

For remote operations, the principal means of information display is through the use of CRTs which can provide a wide range of information in a variety of formats. The RWS is currently capable of presenting televised scenes in color or black and white via two 33cm CRTs and a 127cm large screen display. These CRTs are also capable of displaying alpha-numeric or graphic data in monochrome or polychromatic formats. Additionally, any of the three displays may be used to present a stereoscopic scene to the operator through a field sequential mechanism. Each display has the necessary controls for adjusting contrast, focus, brightness, hue and chroma, and horizontal and vertical picture stability. The two RWS primary displays are mounted in an adjustable panel on the workstation, and the large screen display is above and beyond this panel. The large screen display provides information to the primary operator as well as to interested technical specialists who can view the large screen display without interfering with the operator.

The use of the RWS in the TOREF has generated the following general visual display guidelines which can be applied to other workstations and remote operating situations:

> Providing operators with two primary displays allowed them to focus on the more critical scene or the "better" picture during a remote task. This observation held true even when the two CRTs displayed the same scene. The operator was free to select the clearer picture or the preferred right or left display. The system requirement for redundancy is also served by having two collocated displays.
>
> Operator access to controls for contrast, brightness, stability, and chromaticity is preferred. A detent in the control knobs should be provided to indicate the "set-up" position of the knob to the operator. This is usually halfway between the extremes of the control range and should be at a 12:00 o'clock location.
>
> The capability of adjusting the angle of the primary displays with respect to the operator's normal line-of-sight should be designed into the display mount. The RWS permitted adjustment from 90 degrees vertical (in relation to the Y horizon) to 110 degrees and the TOREF subjects utilized the full range of this adjustment. This adjustment permitted the operators to accommodate for screen glare produced by ambient lighting, seat height, comfortable line-of-sight, and other individual and environmental variables. It is suggested that this degree of flexibility be incorporated into other remote systems workstations. Beyond the advantages for individual operators, this would permit two operators to sit opposite each other and have face-to-face contact when the display panels were in the lower positions.
>
> The visual display arrangement and location should permit the full range of potential operators to manipulate the CRT controls. This was accomplished in the RWS design by having a significant portion of the primary worksurface cut out to create an alcove,

permitting the operator to move into the alcove and be surrounded by the primary worksurface on three sides.

Primary Control Spaces

The types of manual behavior required at a workstation should be considered prior to design. The RWS incorporated two-handed operation as a design criteria. Two hands were required for operation of the primary controls--the translational and rotational hand controllers and the interactive keyboard. The significant differences in the RWS as compared to other workstations are the independent orientation of the keyboard with respect to the primary worksurface and the full forearm support provided for hand controller operation. As noted in the previous section, the TOREF operators utilized the full range of keyboard adjustment and complaints of wrist fatigue were lower during RWS operation than during operation with a conventional workstation. It is recommended that these two features be incorporated into future workstation designs.

The primary worksurface of the RWS was designed for the primary controls required in the TOREF test program (keyboard and hand controllers). Consequently, the RWS did not provide a flat writing surface, storage space near the primary worksurface, or significant space on the worksurface for additional primary controls. Future workstation design should provide for these requirements as necessary. The RWS primary worksurface was designed to physically support the operator and to focus their attention in controlling remote activities. Design generalizations should be made only to similar modes of control over similar tasks.

Secondary Control Spaces

Provisions were made on the RWS for test specific or other specialized controls by including two auxiliary control panels to the right and left of the primary worksurface. These two sloped panels were detachable from the worksurface either to provide additional work space or to reconfigure the secondary controls for specific tests or elements within a test. The auxiliary control panels were within the reach envelope and normal visual angle of the 5th to 95th percentile operator.

The utility of secondary control spaces will be dependent on the specific tasks performed at a workstation. It is recommended that provisions for secondary controls be incorporated into any remote workstation design.

Secondary Displays

Space within the operator's cone of vision should be allocated for secondary displays, which are collocated with their corresponding controls. This was accomplished in the RWS design by allocating space on the wing panels enclosing the workstation. It is generally preferable to limit the number of secondary controls and displays monitored by a single primary operator. Provisions should be made in a workstation design for infrequently used and non-critical controls and displays, but every effort should be made to reduce the actual number. If system and subsystem design dictate that a number of secondary parameters need to be monitored and manipulated, installing these parameters in an engineering monitoring and control console should be considered in order to keep the workload of the primary operator focused on the main control tasks.

Conclusions

The following conclusions were drawn based on the use of the RWS during TOREF tests and simulations and on research findings:

1. Operators strongly agreed that control of seat height and attitude, table height and attitude, and display attitude were important factors contributing to comfort and performance. Provisions should be made for individually setting each of these parameters to the operator's preference.
2. Full forearm support should be provided for the operation of hand controllers. This may necessitate forearm braces, recessed hand controllers, or some similar engineering solution to provide a stable worksurface.
3. Keyboards should be located for bilateral operation. This will generally mean a location directly in front of the operator. Additionally, the attitude of the keyboard should be adjustable with respect to the operator.

4. The locations and attitudes of the workstation components should not be fixed or dictated by the location and attitude of any other component. Each component location should be optimized with respect to all other components in a systematic, as opposed to dogmatic, approach.
5. Engineering convenience should not dictate workstation design if the goal is to accommodate and maximize the capabilities of the human operator. The mere availability of 19-inch equipment racks and flat tables does not justify employing them as workstations for complex, long-duration tasks.

5.0 RECOMMENDATIONS FOR FURTHER RESEARCH

Future research topics were recommended throughout Sections 3.0 and 4.0. These issues will be outlined in this section along with some additional OMV design issues which require investigation in the context of human operator performance.

5.1 OMV Visual System

Camera Location - Determine the effects on operator visual perception and related performance effects of a camera located away from the geometric center of the OMV and bore-sighted on a camera target. Investigate possible interactions of this camera location combined with a pan and tilt perimeter camera.

Camera Field-of-View - Determine the optimal width of the fixed bore sight camera and the variable perimeter camera FOVs. Determine whether position feedback to the operator from the variable FOV is necessary.

Lighting Requirements - Investigate placing light selection (floodlights, spotlights, and combinations) and light intensity under operator control. Evaluate the advantages and disadvantages of a light pointing system which is independent of the camera pointing system.

Stereo Vision - Investigate the effects of reduced frame rate, optical zoom, and degraded resolution on the stereo image and on operator performance.

5.2 Video Bandwidth

Frame Rate - Frame rates between 3 and 5 fr/s should be investigated in conjunction with optical zoom and command time delay. These issues should be evaluated in the context of long-duration tasks and with respect to possible operator visual fatigue.

Resolution and Gray Scale - After the optimal frame rate is determined, reductions in gray scale and resolution may be investigated in an effort to further reduce the video bandwidth required. Degrading resolution should be evaluated only after the frame rate, time delay, and task load issues are resolved.

5.3 Command/Response Time Delay

Variable Interval Time Delay - Determine the effects of variable periods of transmission network caused time delay. The shortest and longest possible delay periods should be determined and varying periods within this range should be introduced into the task in a random manner.

Fixed Interval Time Delay - Determine the effects on performance of the longest predicted time delay period when present at fixed intervals.

Reduced Frame Rate and Time Delay - The optimal frame rate should be included in an evaluation with best case (short duration and fixed interval) and worst case (variable interval) time delays to determine the effects on performance of these combined parameters.

5.4 Ground Control Station

Task Analysis - An item-by-item analysis of all tasks involved in generic and specific OMV missions should be conducted.

Task Allocation - Based on the task analysis, the number of personnel required and their responsibilities should be determined. For example, a primary operator, secondary operator, and engineering console operator may be required or two operators may be sufficient.

Task Density Workload Assessment - A range of tasks, from nominal control of the OMV through emergency recovery of a failed system during docking, should be investigated in simulations to determine the effects of task density on performance by the primary operator and other personnel.

Task Duration Workload Assessment - A range of tasks should be compiled to simulate an OMV mission of realistic duration. This simulation should last long enough for the effects of fatigue to be evaluated.

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6.2 Vision Systems

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6.4 Stereo Vision (Annotated)

Brye, R.G., Henderson, D.E., Pruett, E.C., Shields, N.L., Jr., & Slaughter, P.H. (1978). Earth orbital teleoperator systems Evaluation 1977 year end report (Contract No. NAS8-31848). Huntsville, AL: Essex Corporation.

A study of three camera types for use with a Fresnel stereo system was conducted. The cameras employed in the study were COHU Model 2000, General Electric (GE) TN 2000, and GE, Prototype Charged Induction Device (CID). Five experienced male subjects participated in a target alignment task. Two targets (fixed and moving) were prepositioned in one of three distances from the sensor (fixed 198.12, 223.52, and 248.92cm, moving 203.2, 228.6, and 254.0cm), and subjects were given two trials to align the targets. Data were collected for operator response time and error magnitude. No significant differences occurred for the main effect camera type. A significant difference was found for the interaction of camera type and positions of the fixed target. As a function of the fixed target position, the Prototype CID camera enhanced performance time over the ranges investigated.

A second study evaluated two stereoptic display systems, the Flight Configured Fresnel System (FCFS) and the Piezioelectric Lathanum Lead Zirconate Titanate (PLZT) stereo viewer. The results were combined with data obtained in the first study using the Fresnel lens display system developed by Martin Marietta Corporation (MMC). The procedures were identical to those used in the previous study. Significant differences were found for the main effects fixed target position, initial position of the moving target, and the display system. An interaction effect was found for the initial fixed and moving target positions. For all target positions, mean response time was lowest when the FCFS was used, increased an average of 2.33 seconds when using the PLZT glasses, and was greatest when the MMC Fresnel system was used. For signed error, the interaction of display type and initial position of the movable target was found to be significant. Here the smallest error in alignment occurred when the operator used the FCFS. From these two studies, the authors concluded that if a teleoperator mission required depth perception, the best combination of sensor and display systems seemed to the GE CID camera system and the FCFS.

Fredrick, P.N., Shields, N.L., Jr., & Kirkpatrick, M., III. (1977). Earth orbital teleoperator visual system evaluation program (Contract No. NAS8-31848). Huntsville, AL: Essex Corporation.

Two aspects of this study concerned stereoscopy. The stereo ranging test evaluated the accuracy of operator range estimation using a Fresnel TV system with a three-dimensional (3-D) cursor. It was discovered that the ranging ability of the stereo cursor system resulted in a higher overall error percentage than either of the two monoptic systems previously evaluated. Response time as a function of target range showed a greater time requirement at the two nearest target ranges. Although disparity increases as a function of range, the change in linear disparity over a given change in range decreased with increasing range. The stereo system required triple the performance task time of the monoscopic system. It was concluded that viewing with this system should be limited to areas at or slightly beyond the convergence distance.

The stereoptic test was designed to evaluate an operator's ability to align 3-D targets using vidicon tube and solid state TV cameras as part of a Fresnel stereoptic system. No general differences in response time due to camera type was evident. The effect of fixed target range was the only significant effect isolated. The controlled target was generally positioned at a greater range than that of the fixed target. For target ranges below 225cm, it was shown that response time using the solid state system was significantly lower than for the vidicon system. The researchers concluded that the solid state system is preferable for short distance alignment tasks or tasks where depth judgement was necessary. Human operator performance seemed to be enhanced using the vidicon system for alignment of targets at ranges greater than 230cm.

C-2

Freedman, L.A., Crooks, W.H., & Coan, P.P. (1977). TV requirements for manipulation in space. Man and Machine Theory, 12, 425-438.

The major objective of these studies was to evaluate several alternative video systems in terms of task performance. These systems included a black and white monoscopic system, a color monoscopic system, a stereoscopic system with two black and white cameras, and a two-view black and white system. Using these video systems, operators were required to complete four remote manipulator tasks using toggle switches to control a 4DOF motion mechanism.

The first task was an end effector coupling task which required the operator to move the tip of the end effector into alignment with a socket mounted on the end of a stationary cylinder. The second task was a cylinder docking task, which required a cylinder attached on the manipulator to be moved into coaxial alignment with a stationary cylinder. The third task was a precise positioning task in which the operator moved a small cube from the starting position between two horizontal surfaces and positioned the cube in a marked location on the lower surface. The final task was an obstacle clearance task, which required the subject to transport a large object between obstructing surfaces with little clearance allowed. Two levels of the visual system resolution and four scene parameters were used to modify the four manipulator tasks.

Eight subjects, with normal vision, participated in the study. Three replications of each trial were made. Results indicated that overall performance was best when a two-view system was used. Specifically, the two-view system produced significantly better performance when the dependent variable was positioning error. For performance times, the stereo system produced significantly better performance than using a monoscopic black and white system. Although no significant differences were found, fewer contact errors (contact x seconds) were made when a two-view system and a color mono system were used than for the stereo system and black and white system. Combined relative performance was best for the two-view system, followed by the stereo, color mono, and black and white systems respectively. A significant difference in combined relative performance occurred between the two-view and black and white system. The authors stated, "The overall results of the experiments indicate that for a combination of remote operations, there will be a performance advantage for the two-view system as compared to the other TV systems" (p. 438). However the relative importance of performance as compared with the burden (cost, weight, volume, power requirements, maintainability and reliability) of the system will depend upon the mission in which the remote operation will occur.

Getty, D.J. Introduction: Three-dimensional displays. In D.J. Getty (Ed.), Proceedings of a Symposium on Three-Dimensional Displays, Perceptual Research and Applications to Military Systems (pp. 1-4). Washington, D.C.: National Academy of Sciences.

In an introduction to the proceedings for a symposium on three-dimensional displays, the author provided background information on stereopsis and stereoscopic systems. The perception of depth from a two-dimensional image is obtained as the observer extracts available monocular and coding cue relative to the depths of displayed objects. Depth perception of the three-dimensional image, or stereopsis, results from binocular disparity, where each eye views a scene from a slightly different vantage point. Two classes of stereopsis-based displays were described by the author.

The first class is stereo-pair displays, which are generated by presenting a pair of images containing lateral disparity appropriate for the relative depth of the object. The images are delivered to the eyes by means of mirrors, prisms, cross-polarized glasses, red and green filter glasses, lenticular screens, and alternating shutter glasses. Use of stereo-pair displays requires the viewer to maintain a fixed position relative to the images to avoid the occurrence of visual discomfort. This type of display is used to reconstruct depth without knowledge of object location and actual depth, such as is required in remote viewing of a natural three-dimensional scene.

The second class of stereo displays is a volumetric or space-filling display. These displays are produced by "rapidly rotating a flat dense matrix of LEDs through a volume, [by] holograms, and [by] displays produced by oscillation movements of a flexible, vari-focal mirror" (p. 3). Use of volumetric displays permits the viewer to freely move the head and body, within the limits of the display, to continuously change perspectives of the scene as is done in natural viewing. This type of display is used in simulations or modeling application where depth coordinate information is available.

Grant, C., Meirick, R., Polhemus, C., Spencer, R., Swain, D., & Tewell, R. (1973). Conceptual design study for a teleoperator visual system phase II final report (Contract No. NAS8-29024). Denver, CO: Martin Marietta Corporation

Of particular interest in this report was the section titled "Stereoptic Sensor Simulations". The objective of these simulations was to determine the range and limits of stereo vision (by changing the camera convergence angle, stereo baseline, and field-of-view) and the effects of these limits on operator performance. Maximum and minimum lateral disparity acceptable to the viewer was determined using a special purpose video synthesizer which generated a 2-D spot on the stereo display. By controlling the lateral disparity, the spot separation was increased and decreased such that the viewer's eye convergence angle decreased and increased until the stereo image was disturbing or could no longer be retained. Results indicated viewers could not retain the stereo image when the disparity had exceeded their interpupillary distance.

Studies to define the limits of the sensor baseline and convergence angle were also conducted. By randomly positioning in space several three-dimensional objects, the convergence angle was varied over the range dictated by the maximum and minimum lateral disparity limits. This was done until viewers found the scene disturbing. At this point the baseline was changed, and the process was repeated. Next, the convergence angle was fixed, and the baseline was varied within the predetermined limits of lateral disparity. Performance was variable within and between subjects. The authors found that convergence angles up to and including 15 degrees caused no obvious eyestrain or visual discomfort. Convergence angles above 20 degrees were found to cause a lack of stereo acuity or were visually disturbing. A study was then conducted using a Central Research Laboratories (CRL), Model L manipulator and a task panel. Subjects were to insert an oak block into a sequence of three holes oriented at 0, 45, and 90 degrees off the horizontal. The convergence angle was adjusted so that the line of sight of the two cameras intersected at a distance of 1.81m from the cameras. The baseline and convergence angle were again manipulated. The results indicated as the baseline and convergence angle increased, the task time decreased until the convergence angle was about 15 degrees with a baseline of 45cm. Angles above 15 degrees caused task time to rise sharply. Furthermore, the authors stated that as the baseline increases, stereo acuity also increases until the 45cm baseline is reached.

Using the same manipulator task as above, field-of-view (FOV) was varied. The authors concluded, "the minimal image distortion encountered with a narrow sensor field-of-view is of little importance in light of the increased stereo acuity and monoscopic resolution" (p.IV34). Vertical disparity was examined using both computer generated scenes and real scenes. A vertical disparity of $\pm$ 0.076cm was found to be tolerable for viewers.

The authors concluded by recommending the following stereoscopic sensor system parameters:

Stereo Baseline: 6.4cm
Sensor Convergence Angle: 6.8 degrees
Field of View: 9 to 54 degrees (variable).

Huggins, C.T., Malone, T.B., & Shields, N.L., Jr. (1972). Evaluation of human operator visual performance capability for teleoperator missions. In Ewald Heer (Ed.), Remotely manned systems: Exploration and operation in space (pp. 337-350). Pasadena, CA: California Institute of Technology.

The objective of this study was to identify the specific human visual capabilities that are associated with requirements for teleoperator satellite retrieval and servicing. The aspects of this study that dealt with stereoscopy were the operator's capability to judge depth and to estimate the distance between two offset targets. Five subjects with normal vision were chosen to participate in the study.

The three types of targets used were 2-D stationary, 3-D stationary, and 3-D moving. Each subject was presented with a view of two targets and asked to judge which was nearer and how far apart the objects were separated along the viewing axis. It was determined that the best distance estimation performance was obtained with two monoscopic cameras located orthogonal to each other in the horizontal plane. The researchers also found that single camera (monoscopic or stereoscopic) yielded improved performance when positioned 45 degrees above the work site. Finally, the use of stereo TV yielded no better performance than a single monoscopic camera in all comparable positions.

Malone, T.B. (1971). Final report: Shuttle teleoperator system human factors requirements (Contract No. NASW2220). Alexandria, VA: Essex Corporation.

In a summary of the stereo visual systems for teleoperation, the author recommended use of a monoscopic system with orthogonal views for manipulator capture and satellite servicing. This recommendation was based on the fact that visual discomfort and head constraints are associated with stereo systems and that a lack of hard data exist concerning advantages of stereo over mono systems in remote operation.

Merritt, J.O. (1982). Issues in the evaluation of 3-D display applications. In D.J. Getty (Ed.), Proceedings of a Symposium on Three-Dimensional Displays, Perceptual Research and Applications to Military Systems (pp. 145-149). Washington, D.C.: National Academy of Sciences.

Discussed were many reasons stereo displays have not been proven superior when compared with mono displays. One of the reasons cited was that "the stereo system was a poor quality experimental prototype set up just for the test, while the non-stereo system was a high quality commercial display" (p. 146). In addition, the author stated that in many cases stereo systems were not appropriately set up. Therefore the quality of the picture was degraded, causing eyestrain and discomfort. It was the opinion of the author that only now could conclusive research supporting the benefits of stereo display systems be conducted because state of the art stereo systems are now available for use in the laboratory (systems with visual comfort and resolution equal to non-stereo display systems).

To demonstrate how poor resolution and visual comfort affect subjects' performance, three studies were cited. A 1964 study by Kama and DuMars examined stereo versus mono performance on a simple peg-in-hole task using a through-the-wall, master-slave, remote manipulator with force feedback. TV systems produced stereo and mono images for task performance. No significant differences in performance were found between the stereo and mono systems. In 1964 Chubb replicated the Kama and DuMar study but replaced the TV display systems with direct viewing. Chubb found that performance using two eyes was 20 percent better than performance using one eye. It was reported that although the novelty of one-eyed viewing may have accounted for some of the mono performance degradation, unequal resolution and visual comfort did not confound the results of the study. [The validity of comparing stereo and monoscopic TV viewing with natural stereo produced by the human visual system and monoscopic vision produced by covering one eye is, at best, questionable.]

Also cited were studies by Smith, Cole, Merritt, and Pepper (1979), which are reviewed in this bibliography. The studies cited illustrated the theory that performance using stereo systems is significantly better than using a mono display system. The author concluded by emphasizing the point that the methodology in comparing 3-D and 2-D systems (including a quality stereo system and proper setup) is critical for an appropriate assessment of the costs and benefits of each system.

Pepper, R.L., Cole, R.E., Merritt, J.O., & Smith, D.C. (1978). Operator performance using conventional or stereo video displays. Optical Engineering, 17 (4), 411-415.

The authors conducted three studies comparing the effects of monoscopic and stereoscopic video displays on task performance. In the first study, five male subjects (with normal or corrected vision) completed the Howard-Dolman Two-Rod Depth Discrimination task which utilized three modes of viewing (direct, Fresnel, and Field Sequential). In addition to mode of viewing, the type of viewing (mono or stereo) was also used as an independent variable. For all modes of viewing, angular disparity was less for stereo as opposed to mono viewing. Direct viewing produced the best performance, followed by viewing with the Field Sequential system, and then the Fresnel system (differences between stereo systems were not significant).

The purpose of the second study was to compare the relative performance of the Fresnel and Field Sequential display ability to provide detail for stereopsis. Utilizing stereograms, which were reproductions of Julesz' computer generated random dot patterns that varied in the percent of common units producing depth cues, subjects made 40 judgements of the position of a three-level square under the modes of viewing listed above. Binocularity could be varied between 40 and 100 percent, but the range used in the study was not stated. Stereograms were presented for 15 seconds to maximize stereo cues. Subjects judgements were correct 100 percent of the time when binocularity was 60 percent for direct viewing, 70 percent for the Fresnel system, and 72.5 percent for the Field Sequential system. A secondary study was conducted to control for resolution loss resulting from TV imaging. Two subjects were presented the stereograms for a 5 second interval. No significant differences were found between the Field Sequential and Fresnel systems. The authors concluded that the Fresnel display appeared to be less prone to picture quality deterioration than the Field Sequential system, yet greater fatigue resulted with the Fresnel display due to the rigid, fixed body position and restriction of the head position.

A link task was used for the final study comparing mono and stereo viewing. Stereopsis was produced using a Field Sequential display. The authors failed to define their use of the Field Sequential display or the Fresnel system for this test. Nine subjects (four were experienced remotely manned vehicle operators) participated in an end effector positioning, aligning, and closure task using a CRL Model-L master-slave manipulator. Results indicated that performance was best when the stereo display was used.

Shields, N.L., Jr. & Henderson, D.E. (1981). Earth orbital teleoperator systems evaluation (Contract No. NAS8-31848). Huntsville, AL: Essex Corporation.

Evaluations concerning detectable stereoptic image discrepancy and the effects of stereoptic image discrepancy on task performance were made. Four male subjects were tested. Subjects were seated in an isolated viewing room that was equipped with a Fresnel lens, two channel TV display and a remote zoom lens control for either the left or right camera. The subjects' task was to manipulate the size of one of the images using the zoom control to eliminate any perceived image discrepancy. It was determined that the mean errors between the two displayed target areas can be 1.8 percent and still be considered as being equal by the operator. A trend was also noted in that alignment error increased at a gradual rate as image discrepancy also increased.

Shields, N.L., Jr., Kirkpatrick, M., III, Fredrick, P.N., & Malone, T.B. (1975). Earth orbital teleoperator visual systems evaluation program (Contract No. NAS8-30545). Huntsville, AL: Essex Corporation.

Two studies were conducted to evaluate range estimation under monoptic and stereoptic viewing conditions. The objective of the first test was to determine the operator's ability to position a variable target at the same range as a fixed target utilizing either a monoscopic or a Fresnel stereo display system. A 2DOF target motion generator

(TMG) was used to align a variable target with a fixed target. The TMG was controlled from a box containing a two position travel direction switch and a knob which controlled the rate applied by the direction switch. Operators controlled the TMG from behind a curtain with visual input from the display system (Fresnel stereo or a mono system). The independent variables were target/background contrast, lateral fixed target placement, fore/aft placement of the fixed target, initial position of the variable target, and video system modes.

Each of the four subjects received all 72 combination of the independent variables, with the display modes presented in blocks and counterbalanced to control for learning. The remaining variable levels were randomized in blocks. Each subjects was instructed to maneuver the variable target via the TMG control box. When the subject judged the variable and fixed target to be aligned, a response key was depressed which stopped the timer and terminated the display.

Response time and adjustment error data were collected and analyzed. The grand mean alignment error for both stereo and mono systems was found to be significantly different from zero ($p < .05$). This indicated that there was a tendency to place the variable target closer to the fixed target or to overshoot the range. The interaction of camera system type and the side of the fixed target on which the variable target was located was significant ($p < .01$). The authors suggested that a problem of false depth cues while using the mono system may have caused this significant difference. It appeared that the subjects utilized brightness cues resulting from a small right-left brightness difference which could not be controlled in the laboratory. Using absolute error as the dependent variable, no significant differences were found, but mean absolute error for the mono system was more than three times that for the stereo system. For response time, a significant difference occurred due to the TMG travel distance relationship which depended on the fixed target position and the TMG initial position.

A similar study was conducted which employed varied video system parameters. The camera was placed in plane with the translational axis but was offset 45 degrees to the left of the TMG translational plane. A GRC Random Noise Generator was used to introduce radio frequency (RF) noise with the video signal. A Computer Labs analog/digital and a digital/analog converter was used to provide a 4 bit digital transmission format, and a narrow band pass filter was installed to allow transmission to be limited to 1 MHz. The independent variables manipulated in the study were target/background and target/target contrast, initial position of TMG target, initial position of the fixed target, signal/noise ratio and video transmission. The same subjects who participated in the previous study were involved in this study. The subjects were signaled to begin, aligned the targets, and depressed the response key to indicate the task had been completed. Analyses of variance on mean errors, mean absolute errors, and response time were computed. Significant differences were found for the interactions of contrast and signal/noise ratio ($p < .05$), fixed target position, contrast, and transmission mode ($p < .05$), fixed target position, contrast, transmission mode, and signal/noise ration ($p < .05$), and fixed target position, contrast, transmission mode, and initial variable target position ($p < .05$). These findings showed that the video systems tested were quite insensitive to bandwidth reduction on one channel or to reduction in signal/noise ratio in terms of constant error. For the dependent variable, absolute error, significant differences were found for fixed target position ($p < .05$), transmission mode ($p < .05$), and for the interaction of contrast and transmission mode ($p < .05$). For response time, significant effects of the independent variables were found to be those associated with obvious correlations between the initial variable target position, the fixed target position, and the TMG travel speed.

The authors concluded that subjects performed equally well with the stereo and mono systems when there was an angle between the camera viewing axis and the motion axis, thus, causing the target separation to become a lateral dimension on the display. The authors also stated that reliance on stereoscopic cues clearly increased as the viewing angle decreased. In addition, the accuracy of the ability to detect the relative range between two target objects (range resolution) decreased with increasing viewing angles for both video systems. However, the decrease would be greater for the mono TV system.

Smith, D.C., Cole, R.E., Merritt, J.O., & Pepper, R.L. (1979). Remote operator performance comparing mono and stereo TV displays: The effects of visibility, learning and task factors (Technical Report No. 380). San Diego, CA: Naval Ocean Systems Center.

Three experiments were conducted to compare task performance using stereo versus mono display systems. Apparatus employed in the experiments included a CRL Model G, master-slave manipulator, a modulation transfer function (MTF), and a piezioelectric lathanum lead zirconate titanate stereoscopic viewer. The MTF was used in these experiments to simulate different levels of visibility. The PLZT viewer utilized an electro-optic shutter effect that operated on the principle of alternately blocking and unblocking the perspective view for each eye.

In the first experiment, subjects were required to position the manipulator arm to pick up one peg from the starting block at the right front of the taskboard, grasp the peg, move to one receiving block and insert it, then place the second peg in the second block, etc. Six extensively trained subjects participated in 10 stereo and 10 mono tasks (a different position was used for each task, and each task was completed under three levels of visibility--clear followed by moderate then severe). The results indicated that performance time was better when stereo was used under all visibility conditions ($p < .0025$). The authors reported that performance using the mono system might have been better had the camera been closer to the task so that critical features were more finely resolved. Although performance was best when the stereo system was used, reduced resolution, bothersome visual noise, and loss of stereo when the eye-base was no longer parallel with the eye-base on the screen also occurred when the stereo system was employed.

A second experiment was conducted which replicated the methodology of the first, but inexperienced subjects were used. Sixteen Naval Ocean Systems Center (NOSC) employees were used as subjects. These subjects were instructed to place the pegs in the respective hole, being extremely careful not to drop the peg or make unnecessary contact with the taskboard. A mixed factorial design was used for this experiment with display type as the between-groups factor and visibility and trials as the within-groups factors. Significant differences occurred for the visibility factor for both performance time and errors. No significant differences occurred between the mono and stereo display systems. More errors were observed for stereo in all visibility conditions. The authors stated that due to a lack of sensitivity in the between-groups design, the high degree of inter-subject variability in performance across all trials was responsible in part for the lack of a significant difference between the stereo and mono systems.

The third experiment involved a task designed to represent line attachment, sample gathering, and certain salvage tasks. In this task, the taskboard surface was irregularly shaped and embedded with hoops to represent marine growth and corrosion. Twenty NOSC employees with previous remote manipulator experience were instructed to thread a 1/2 inch rope through two hoops designated by the researchers. Ten trials were attempted under severe, moderate, and clear visibility conditions. Performance times were 50 percent longer when the mono display was used, and twice as many errors occurred. Significant differences were found for the main effects mono-stereo and visibility and for the interaction of mono-stereo and visibility. The authors concluded that stereo systems provided significant advantages over mono systems as visibility and task object complexity become more difficult.

Tewell, J.R., Polhemus, C.E., Skidmore, R.A., Grant, C., Meirick, R.P., O'Connor, W.J., Rittenhouse, D.L., & Schlaht, A. (1972). <u>Conceptual design study for a teleoperator visual system: Vol. 1 technical proposal</u>. Denver, CO: Martin Marietta Corporation.

Discussed in this proposal were various visual systems which may be employed for use in teleoperation. Three major visual systems were described: direct view, monocular television, and stereo television. Direct view, as through a window of the Shuttle or Space Station, would be the most acceptable to a flight crew because it would be a reliable and natural system. Limitations of direct viewing included a restricted FOV due to obstructions and the requirement for operators to be physically close to the work site. Monocular TV, which consisted of a TV system and an optical radar system included for range/rate information, optimized resolution, bandwidth, power, mass dimensions, and controls, but allowed no depth information to be relayed to the operator. Stereo TV was compared to direct viewing, in which all human visual perception capabilities such as intensity, position, color, and depth information were realized.

Four types of stereo display systems were described in detail. One display was the Fresnel Display Screen developed by Martin Marietta Corporation. This system consisted of two monitors (one of each stereo image), two imaging lenses, and a Fresnel display screen. Images from the two monitors were projected through the imaging lenses onto the Fresnel display screen to produce stereopsis. According to the authors, the advantages included optimized image illumination, use of no glasses or other viewing aids, a FOV which could be designed to accommodate nearly full peripheral vision, no refocusing of the eyes, retention of all resolution and color information, and a simple and compact system. The only disadvantage reported was that head movements are restricted to ±7.62cm of vertical movement and ±15.24cm of forward movement.

The second type of stereo display discussed was the Lenticular Display. This display is similar to the Fresnel system. Linear mixing grids are placed over the face of each monitor to divide the pictures into strips. The images are then combined via beamsplitters and imaged onto the diffuse screen with right and left image lines interlaced. The lenticular faceplate divided the right and left image line elements into zones so that a properly positioned viewer could see a stereo image. The advantages reported for this system were that no glasses were required, color information was retained, and vision of peripheral displays and/or instruments were not impaired. The disadvantages listed for this system were reduced resolution, reduced FOV, and image brightness which was not maximized.

The Polarized Display was the third type of stereo system described. This display employed dual monitors that projected images into cross polarized filters which were used to separate the right and left stereo images onto a monitor. Cross polarized glasses were used to separate the right and left stereo images. Advantages of this system included resolution quality and color information which was similar to that of the Fresnel system. The disadvantages of the Polarized Display are that the cross polarized glasses caused eyestrain and confusion when viewing peripheral instruments and displays and poor illumination efficiency.

The final display system described was the Color Separated Display. The two images from the monitors were color-coded and electronically superimposed onto a single color monitor. Color-coded glasses were then worn to produced stereo vision. The advantage was that if narrow frequency bandstop filters were used in the glasses, eyestrain would be minimal in viewing peripheral objects. The disadvantages were that color information was lost and the stereo image was disturbing due to the nature of the color-coded glasses employed to produce the stereo image.

Tewell, J.R., Ray, A.M., Meirick, R.P., & Polhemus, C.E. (1974). Teleoperator visual system simulations. Journal of Spacecraft, 11(6), 418- 423.

Three evaluations comparing a stereoscopic and monoscopic TV system were conducted for application in teleoperation visual and motion simulations. The first study evaluated the subjects ability to align two objects in a common plane. The independent variables were viewing dimension (stereo versus mono), viewing angle (30 degree vertical and horizontal offset, and set at the line of motion), and object size and shape. The stereo system employed in this study was a Fresnel stereo system. The results indicated that stereo proved to be consistently better throughout the test. Camera offset had a greater negative effect on monocular viewing, with the horizontal offset producing the worst performance. Objects of different size caused greater performance degradation when a mono system was used.

The objective of the second study was to evaluate performance on two manipulative tasks in order to compare a stereo system with a two-view mono system, and to examine the effects of camera location and lighting on task performance. Using a CRL Model L, master-slave arm with a general purpose alligator jaw type end effector, the four subjects were to grasp a block in the right hole of a task board, remove it, insert it in the left hole, then repeat the process to place the block into the middle hole, and then into the right hole and leave it. An additional manipulative task required subjects to grasp a drawer in the top guide of a taskboard, remove it, place it in the bottom drawer, then in the middle, and then back in the top guide. The independent variables used in this study were viewing dimension, camera location, number of views, and lighting. Based on performance, comments and forced-choice rankings, the authors stated, "the operators would learn the task so they could eventually perform it with much degraded visual cues using kinesthetic feedback. Therefore, task times were somewhat misleading, and subjective comments were more reliable indicators of task difficulty" (p. 420). It was concluded that stereo was better than mono for all camera locations, and that one stereo view was preferable over two mono views. In regard to camera location, a 45 degree offset to the right was preferable for a one-view stereo system. For a one-view mono system, camera location was preferable at the line of motion because angle estimation problems occurred otherwise. No camera locations were suggested for a two-view system. The authors stated that lighting was a critical variable in task performance yet failed to report any definitive findings regarding lighting location and intensities.

The third simulation was conducted to investigate remote viewing requirements associated with retrieving a spinning and nutating satellite. A Martin Marietta Space Operations Simulator was used in this study. The simulator was a 6DOF servo-driven, computer-controlled device which used a gimbaled attitude head to produce three rotational DOF and a moving base to produce three translational DOF. A mathematical model was appropriately scaled on an analog computer with the signals applied to the moving base and the attitude head of the simulator. The moving base was piloted from a control station. The task was completed in two phases. The first phase consisted of estimating the nutation angle and rate and to establish spacecraft alignment with the nutation axis of the satellite. The second phase required the subject to extend and rotate the retrieval manipulator arm to match the estimated nutation angle and rate, and then a final tracking of the satellite spin axis was performed. Subjects preferred the monocular view because it allowed freedom for head movements, resulted in less fatigue, and provided better resolution. However, the authors reported that the stereo system produced better alignment.

Conclusions drawn from this study were that stereoscopic systems permit adequate alignment of objects regardless of differences in viewing angles and object size and shape. For manipulation tasks a two-view monoscopic system and a stereoscopic system were approximately equivalent. The authors recommended a stereo TV system with a Fresnel display for teleoperation. They further stated that visual systems are strongly influenced by the tasks required of the teleoperator. Specific recommendations and results of these studies should be considered in light of the fact that the recommended Fresnel system was developed by Martin Marietta Corporation, and the results are based solely on descriptive statistics and subjective opinions. Due to the lack of inferential statistics, no generalizations should be made from the test results.

6.5 Ground Control Station (Annotated)

Anthropometric source book volume 1: Anthropometry for designers. (1978). Lyndon B. Johnson Space Flight Center, TX: National Aeronautics and Space Administration, NASA Reference Publication No. 1024.

This publication provides a comprehensive tabulation of anthropometric data. Volume 1 covers basic areas of anthropometry and its application to the design of workspaces, clothing, and equipment. The document includes dimensional anthropometric data on 59 variables for 12 selected populations.

Beldie, I.P., Pastoor, S., & Schwarz, E. (1983). Fixed versus variable letter width for televised text. The Journal of the Human Factors Society, 25(3), 273-277.

Variable matrix, a character design in which narrow letters (such as "i") occupy less space than wide letters (such as "m"), resulted in improved efficiency on two out of three tasks. This design was recommended for television screens.

Billmayer, H., Rodriguez, R.C., & Wheeler, S.C. (1983). Terrain edit system/evaluation matrix processing system (TES/EMPS) human engineering study. Huntsville, AL: Essex Corporation.

The authors evaluated two VDT workstations from a human factors engineering standpoint. Their recommended workstation dimensions were: 27 in. to 33 in. (685.8mm to 838.2mm) from top of screen to seat; 42 in. to 51 in. (1066.8mm to 1245.4mm) from top of screen to floor; 25 in. to 30 in. (635mm to 762mm) from floor to table top. The maximum recommended viewing distance was 27.6 in (701mm) with an optimum distance of 15.8 in. to 19.7 in. (401.32mm to 500.38mm). The optimum eye level was found to be even with the top of the screen. The minimum acceptable lighting level at the workstation surface was 540lx (50 ft/c) and the recommended level was 755lx (70 ft/c).

Bury, K.F., Boyle, J.M., Evey, R.J., & Neal, A.S. (1982). Windowing versus scrolling on a visual display terminal. The Journal of the Human Factors Society, 24(4), 385-394.

In most cases, subjects in the "window" display groups performed significantly faster and with significantly fewer moves than subjects in the "scroll" display groups.

Cahill, M. & Carter, R.C. (1976). Color code size for searching displays of different density. The Journal of the Human Factors Society, 18(3), 273-280.

Twenty subjects searched for three digit numbers in displays ranging from 10 to 50 items in density and coded in 1 to 10 colors. Search times increased linearly with density and curvilinearly with the number of colors. Adding colors to the display reduced search times until approximately seven colors were used, after which, search times increased.

Carter, R.C. (1979). Visual search and color coding. Proceedings of the Human Factors Society - 23rd Annual Meeting, 369-373.

Search time increased by one order of magnitude when the number of display items in the target's color increased from one to the display density. Items not of target color affected search time only to the extent that their color was similar to target color. Personnel characteristics - ability and experience - were unrelated to search speed.

Chao, B.P., Beaton, R.J., & Snyder, H.L. (1982). Evaluation of CRT displayed digital imagery using subjective scaling. Proceedings of the Human Factors Society - 26th Annual Meeting, 329-333.

Researchers investigated perceived interpretability of two digital image degradations - blur and noise. Ten scenes, each degraded by five levels of blur (20, 40, 80, 160, and 320 micrometers) and five levels of

noise (200, 100, 50, 25 and 12.5 s/n ratio), yielded 250 images displayed on a CRT. As perceived by 15 photointerpreters, the blur, noise, and interaction effects were significant. At the two lowest blur levels and the two highest signal-to-noise ratios there were no differences in interpretability. Otherwise, the reduction in interpretability was more distinct with increased degradation. In non-noise images, the addition of blur decreased interpretability in a linear fashion. With noisy images, the impact of adding blur was lessened.

Christ, R.E. (1975). Review and analysis of color coding research for visual displays. The Journal of the Human Factors Society, 17(6), 542-570.

A review of 42 studies between 1952 and 1973 found that color coding may be a very effective performance factor in some cases and detrimental in others. Color aided both identification and search if the color code was known in advance and unique to the target. A problem occurred when color was used in multidimensional displays; specifically, when colors were added to an achromatic display, the subject's ability to identify achromatic targets decreased.

Dainoff, M.J., Happ, A., & Crane, P. (1981). Visual fatigue and occupational stress in VDT operators. The Journal of the Human Factors Society, 23(4), 421-438.

One hundred and twenty-one office workers reported relatively high levels of incidence of eye fatigue symptoms and complaints of glare and lighting. Complaints appeared to be independent of job pressure and hostility to computerization.

Dodson, D.W. & Shields, N.L. (1978). Man/terminal interaction evaluation of computer operating system command and control concepts. Proceedings of the Human Factors Society - 22nd Annual Meeting, 388-392.

No significant differences were found between menu, command key, and multi-display concepts. The authors recommended that some combination of command key and multi-display concepts would provide the best definition for an ECOS command and control service scheme in terms of human-terminal interaction.

Dodson, D.W. & Shields, N.L. (1979). Development of display design and command usage guidelines for Spacelab experiment computer applications. Proceedings of the Human Factors Society - 23rd Annual Meeting, 70-74.

With regard to display density, the researchers found the response times increased rapidly as display density exceeded 60%. No relationship was observed between display density and number of operator errors. Columns that were functionally arranged had lower response times. There was no difference in response times related to the percent of dynamic display parameters.

Emmons, W.H. & Hirsch, R.S. (1982). Thirty millimeter keyboards: How good are they? Proceedings of the Human Factors Society - 26th Annual Meeting, 425-429.

The study compared keyboard heights of 30, 38, and 45 millimeters above a table top 72 centimeters from the floor. Performance on the higher keyboards was significantly superior to the 30 millimeter height. Questionnaire data showed significant operator preference for the higher keyboards.

Grandjean, E., Hunting, W., & Piderman, M. (1983). VDT workstation design: Preferred settings and their effects. The Journal of the Human Factors Society, 25(2), 161-175.

In this field study, 68 subjects employed by four different companies performed their regular jobs using a workstation with an adjustable CRT, keyboard, and chair. Subjects were free to adjust the components at any time during the study. Preferred settings were consistent across the five days of the study. Seat heights ranged from 44 to 54cm and keyboard heights ranged from 73 to 97cm. The preferred CRT angles ranged from 88° to 103° with a mean of 94°. Questionnaire data revealed that complaints of tension or impairment of the neck, forearm, shoulders, back, and wrists were much lower in the preferred settings than in a nonadjustable setting.

Habinek, J.K., Jacobson, P.M., Miller, W., & Suther, T.W. (1982). A comparison of VDT antireflection treatments. Proceedings of the Human Factors Society - 26th Annual Meeting, 285-289.

Three antireflection treatments - a micromesh filter, a quarter-wave length thin film, and an etched face plate - did not differ in terms of effectiveness. All were preferred to an untreated screen.

Isensee, S.H. & Bennett, C.A. (1983). The perception of flicker and glare on computer CRT displays. The Journal of the Human Factors Society, 25(2), 177-184.

Results suggested that low to moderate levels of ambient illuminance (approximately 100-260lx) and moderate levels of video luminance (65 cd/m^2) minimized discomfort due to direct glare, reflected glare, and flicker. Video luminance appeared to be a much greater factor in producing flicker and glare than ambient illuminance. A filter over the face of the CRT was suggested.

Kirkpatrick, M., Shields, N.L., Malone, T.B., & Guerin, E.G. (1976). A method and data for video monitor sizing. Proceedings of the 6th Congress of the International Ergonomics Association, 218-221.

Analytical methods based on operator performance were used to establish monitor size requirements for a particular application. Formulas for determining monitor size as related to viewing distance, target size, distance from target to camera, and field of view width were developed. Authors suggested that because viewing distance is not constant a useful approach is to plot the equations over a range of viewing distances. The researchers stated that larger monitors will not produce improved performance due to resolution limits.

Knowles, W.B., & Wolfeck, J.W. (1972). Visual performance with high-contrast Cathod Ray Tubes at high levels of ambient illumination. The Journal of the Human Factors Society, 14(6), 521-532.

Trace brightness required to perform the visual tasks was primarily a function of the reflectances and resulting background brightness of the CRT faces. Background brightness was determined by the reflectance of the CRT face.

Kolers, P.A., Ducknicky, R.L., & Ferguson, D.C. (1981). Eye movement measurement of readability of CRT displays. The Journal of the Human Factors Society, 23(5), 517-527.

Smaller characters (70 per line as opposed to 35) and static page display were preferred for efficiency of reading.

Kopala, C.J. (1979). The use of color-coded symbols in a highly dense situation display. Proceedings of the Human Factors Society - 23rd Annual Meeting, 397-401.

Redundant color-coding (both color and shape coded) significantly reduced response time and error rate compared to color or shape coding alone.

Martin, M.F., Shields, N.L. & Rodriquez, R.C. (1984). The Reconfigurable Workstation, short task comparative analysis. (Test Report No. 11-84-RWS-01). Huntsville, AL: Essex Corporation.

This study compared a standard teleoperator workstation with the Reconfigurable Workstation (Shields & Fagg, 1984). A keyboard input task and a hand controller, cursor positioning task were performed by 12 subjects on both workstations. No significant differences in task performance occurred due to the workstation used. Subjects reported increased tension of the wrists when tasks were performed on the standard workstation. The RWS was designed to maximize operator comfort during long-duration teleoperation tasks. It was concluded that the task duration of 20-25 minutes in the test was not sufficient to induce operator fatigue, thus no difference between the two workstations occurred.

Miller, W. & Suther, T.W. (1983). Display station anthropometrics: Preferred height and angle settings of CRT and keyboard. The Journal of the Human Factors Society, 25(4), 401-408.

Thirty-seven subjects ranging in anthropometric characteristics from the 5th to the 95th percentiles of the population were placed in a work setting with a CRT, keyboard, and chair. The subjects performed a text input task after adjusting each of the three workstation components to their preferences. A -0.71 correlation between seat height and keyboard angle indicated that the standard fixed keyboard angle of 15° may be inappropriate for operators who prefer low seat heights. Preferred keyboard slopes ranged from 14° to 25° with a mean of 18°. Keyboard heights ranged from 63 to 78cm and CRT heights ranged from 81 to 104cm (measured from floor to center of CRT face). The authors suggested that the CRT angle be adjustable from -5° to 20°.

Mourant, R.R., Lakshmanan, R., & Herman, M. (1979). Hard copy and cathode ray tube visual performance - Are there differences? Proceedings of the Human Factors Society - 23rd Annual Meeting, 367-368.

In this study, visual fatigue increased as a function of time as compared to copy. The amount of information processed had an effect on fatigue. The authors found that larger amounts of information processed produced greater visual noise in peripheral vision requiring longer rest periods. Low display contrast was shown to increase fatigue.

Pastoor, S., Schwarz, E., & Beldie, I.P. (1983). The relative suitability of four dot-matrix sizes for text presentation on color television screens. The Journal of the Human Factors Society, 25(3), 265-272.

The authors tested characters with four dot-matrix sizes (5x7, 7x9, 9x13, and 11x15). In all tasks, the smallest size elicited the worst performance. Qualitative performance was equal for all sizes, however, time varied up to 20%. The 9x13 size (9 horizontal rows of 13 dots each), which subtended an angle of 17 minutes of arc, was rated significantly better than the smaller sizes.

Shields, N.L. & Fagg (Martin), M.F. (1984). Analysis and selection of a remote docking simulation visual system. (Contract NAS8-35473 Final Report No. H-84-04). Huntsville, AL: Essex Corporation.

This report describes the design of the Reconfigurable Workstation (RWS). The RWS was developed for use in the Teleoperator and Robotics Evaluation Facility at NASA's Marshall Space Flight Center. The design was based on findings from human factors research concerning the impact of workstation design on operator performance. The RWS accommodates operators ranging in size from the 5th percentile U.S. female to the 95th percentile U.S. male. The RWS provides three CRTs, two hand controllers, a keyboard, and auxillary controls and displays. The workstation is reconfigurable with respect to the individual operator and to specific task requirements.

Shields, N., Piccione, F., Kirkpatrick, M. & Malone, T.B. (1982). Human Operator Performance of Remotely Controlled Tasks: A Summary of Teleoperator Research Conducted at NASA's George C. Marshall Space Flight Center Between 1971 and 1981. Huntsville, AL: Essex Corporation.

The authors reported that high contrast, analog signals and adequate signal-to-noise (S/N) separation yield the best recognition of shapes and patterns. Target to background contrast was determined by the following formula:

$$\% \text{ contrast} = 100 \times \frac{(\text{R of B}) - (\text{R of T})}{\text{R of B}}$$

where R = reflectance, B = background, and T = target.

Brightness discrimination between two targets was enhanced by contrast values of .25. For size discrimination between two targets, contrast ratios of .6 should be used. Analog signals were found to enhance visual acuity, brightness discrimination, and character recognition. Character recognition was also improved by high contrast and a 32 dB S/N. The character font recommended was futura demibold with a character height of 30 arc min., character width of 23 arc min., and stroke width of 5.5 arc min. S/N below 15 dB significantly degraded performance while a S/N above 21 dB did not exert a negative influence. Orthogonal monoptic camera pairs yielded good results in judgment of separation of targets. Split field stereoscopic systems yielded less accurate results.

Shute, S.J. & Starr, S.J. (1984). Effects of adjustable furniture on VDT users. The Journal of the Human Factors Society, 26(2), 157-170.

Fifty-seven telephone operators served as subjects in this eight-week field study of advanced furniture design for VDT workstations. The advanced work table and chair were characterized by dimensions that were easily adjustable by users in comparison to a conventional table and chair which provided no means of adjustment or inconvenient adjustments that could only be made with difficulty. Four combinations of advanced and traditional components were compared. Although on-the-job discomfort was reduced when either of the traditional components was replaced by an advanced component, the effect was far greater when the advanced chair and table were used in combination. Each adjustment on the advanced workstation was used by at least 70% of the subjects every day. Subjects reported statistically significant reductions in discomfort and intensity of discomfort in 8 out of 15 areas of the body. The authors concluded that because working posture is heavily dependent on the task performed, the ease of adjusting the advanced station was the most influential factor in the obtained results.

Sidorsky, R.C. & Parrish, R.N. (1980). Guidelines and criteria for human-computer interface: Design of battlefield automated systems. Proceedings of the Human Factors Society - 24th Annual Meeting, 98-102.

The authors devised a format for recasting human factors data into a form that makes it more digestible for other members of the design team.

Stammerjohn, L.W., Smith, M.J., & Cohen, B.G.F. (1981). Evaluation of work station design factors in VDT operations. The Journal of the Human Factors Society, 23(4), 401-412.

An onsite evaluation at five establishments examined VDT workstation designs and compared them to recommendations in the literature. Design factors evaluated were keyboard height, screen position, illumination, and glare. Ambient illumination of 500-700lx was found to be acceptable. Problems encountered were excessive keyboard height (75cm from floor to home keys), screen angle (a 10-20 degree angle was recommended), and reflected glare. The authors recommend that the keyboard be placed at or below elbow height to reduce forearm fatigue. Elbow height varies between the 5th and 95th

percentiles from 60.5cm to 82.0cm; therefore, the authors recommend a wide range of adjustability in workstation designs.

Suther, T.W. & McTyre, J.H. (1982). Effect on operator performance of thin profile keyboard slopes of 5°, 10°, 15°, and 25°. Proceedings of the Human Factors Society - 26th Annual Meeting, 430-434.

An IBM Datamaster (System 123) keyboard was set at a 5°, 10°, 15°, and 25° angle on a table top 685.8mm from the floor. Sixteen experienced subjects typed in each of the four conditions. No significant differences were found in performance. Subjects reported that the keyboard was uncomfortable at 5° and 25° and that they noticed no difference between 10° and 15°. The authors recommended a setting of 10°-18°.

Tullis, T.S. (1980). Human performance evaluation of graphic and textual CRT displays of diagnostic data. Proceedings of the Human Factors Society - 24th Annual Meeting, 310-316.

Four CRT display formats - narrative text, structured text, black and white graphics, and color graphics - were evaluated with respect to speed and accuracy of response. Accuracy did not vary with display. Initially, response to graphic formats was faster. With additional practice, response to textual formats was just as fast as response to graphics.

Tullis, T.S. (1981). An evaluation of alphanumeric, graphic, and color information displays. The Journal of the Human Factors Society, 23(5), 541-550.

Speed and accuracy of subjects interpreting alphanumeric, graphic, and color coded displays were measured. Accuracy did not vary with format. Response time for graphic formats was consistently shorter than for the narrative format. No significant difference was found in response times for black and white versus color graphics.