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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

Prepared For:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared By:

Nicholas Shields, Jr.
Frances Piccione
Mark Kirkpatrick, III
Thomas B. Malone

ESSEX CORPORATION
3322 South Memorial Parkway
Huntsville, Alabama 35801

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FOREWORD

For the past eleven years, NASA's Marshall Space Flight Center (MSFC) has been conducting the Teleoperator Technology Development Program which has identified critical operator/machine interactions that must be incorporated into teleoperator systems from the initial design stages. The work accomplished under the technology development program is the product of scores of dedicated people, but special recognition is due Mr. Wilbur Thornton and Mr. Edward Guerin for their leadership in this program as contract technical monitors.

While this is a summary document of work over the past ten years, it is felt that it will also serve as an initial chapter for work which needs to be accomplished through the next ten years as we strive to make the space environment more productive.

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ACRONYMS AND ABBREVIATIONS

ADAMS	Advanced Dexterous Anthropomorphic Manipulator System
A/D	Analog to Digital
b/s	Bits per Second
CCD	Charged Coupled Device
CCTV	Closed Circuit Television
CFF	Critical Flicker Frequency
CID	Charged Induction Device
CRT	Cathode Ray Tube
D/A	Digital to Analog
dB	Decibel
DOF	Degree(s)-of-Freedom
ESAM	Extendible Stiff Arm Manipulator
EVA	Extravehicular Activity
f	Frequency
FPS	Frames Per Second
g	Gravity
I	Intensity
L	Lamberts
LSS	Large Space Systems
MATH	Mechanically Actuated Trigger Hand
MDA	Multiple Docking Adapter
MHz	Mega Hertz
MIT	Massachusetts Institute of Technology
mL	Millilamberts
MSFC	Marshall Space Flight Center
MU	Mobility Unit
NASA	National Aeronautics and Space Administration
NBS	Neutral Buoyancy Simulator
PFMA	Protoflight Manipulator System
PLZT	Piezoelectric Ceramic Lead Lantham Zirconate Titinate
RF	Radio Frequency
RMS	Remote Manipulator System
S/N	Signal to Noise
TKA	Terminal Kit Adapter
TMS	Target Motion Simulator
TRS	Teleoperator Retrieval System
TV	Television
VDT	Video Display Terminal
Vdc	Voltage Direct Current

1.0 INTRODUCTION

This document presents a description and the results of investigations conducted by Essex Corporation for the George C. Marshall Space Flight Center's Teleoperator Technology Development Program between 1971 and 1981. It also describes the capabilities within the teleoperator laboratories to perform remote and teleoperated investigations for a wide variety of applications.

Essex Corporation has been under contract to NASA since 1971 to define a program of technology development for the human control of remote operations; to conduct laboratory experiments, investigations and evaluations, the purpose of which is to define design criteria for teleoperators; and to promulgate this information to organizations with an interest in remote operations, teleoperation and automation. The volume of technical information has grown so large that this consolidated document was developed as an introduction to teleoperation and as a summary of pertinent laboratory findings which help to define design criteria and provide evaluation data for specific teleoperator subsystems.

This report addresses three major teleoperator issues: the human operator, the remote control and effecting subsystems, and the human/machine system performance results for specific teleoperated tasks.

1.1 GENERAL DESCRIPTION OF TELEOPERATOR SYSTEMS

As a system which extends and enhances the human's capabilities, teleoperators take on numerous forms and perform many functions, but each shares the characteristics of: (1) local human command/control; (2) communication control and feedback interfaces; and, (3) remote mechanical effectors for mobility and manipulation.

The most commonly proposed teleoperated applications involve significant distances between the control station and the effecting or actuating unit, as in undersea operations, mining, remote nuclear operations, and space orbital applications, but these do not preclude defining human-attached systems such as exoskeletal work amplifiers or prosthetic devices from being included in the general class of teleoperators. Further, where remote systems are partially managed by preprogrammed computer subroutines and the human operator maintains a supervisory or override capability, these systems could fall under the general category of teleoperator as opposed to autonomous systems such as robots.

In order to extend the human's capability to perform tasks, teleoperator systems have major subsystems for the control, command, transmission and execution of tasks, these being:

1. Operator's Control Station with provisions for remote scene feedback via television, provisions for remote system mobility via hand controllers or switches; provisions for manipulation via hand controllers; and provisions for system status monitoring via indicator lights, meters, computer printouts, and video display terminals (VDT's).

2. Interface Unit for transmitting and receiving communications between the operator and the effector unit, for computational assistance in coding, decoding commands and activities, and for transformation of data between the operator and effector unit.

3. Effector or Actuator Unit for mobility about, sensing, and manipulation of the remote environment. The most frequently proposed sensors are television cameras with onboard lighting. Proposed mobility subsystems depend upon application, but generally permit movement in six degrees-of-freedom (DOF) for the unit. The manipulative devices will generally reflect the nature of the task from simple scooping of planetary samples to complex assembly, servicing, and repair activities.

While the specific subsystems employed to accomplish teleoperated tasks may vary greatly, each teleoperator system can be viewed as an integrated system of these three major areas. The utility in treating teleoperator systems as an integrated operator/interface/effector system is a function of the particular capabilities and limitations of each of the three areas which must be structured to take the greatest advantage of the capabilities, while compensating for the limitations (Ref. 1).

1.2 CAPABILITIES AND LIMITATIONS OF MACHINE SYSTEMS

The impressive accomplishments of making "smart" machines notwithstanding, there are very real limitations imposed when relying upon machine performance at a remote site. Even when employing artificially intelligent machines, terms of cost and reliability must be considered as limitations. On the other hand, machines have some capabilities that far exceed those of any human, and these are what we want to exploit in teleoperator systems. Table 1-1 gives an overview of machine capabilities and limitations derived from several human factors sources. With some certainty, the capabilities of machines to react more flexibly will be forthcoming, and as this occurs, the limitations of machines must be modified.

At the other end of the teleoperator system, we must deal with the capabilities and limitations of the human operator, which are not so amenable to change.

1.3 CAPABILITIES AND LIMITATIONS OF HUMANS

While the uniqueness of the human organism has long been recognized in a philosophical sense, it is not often treated in terms of specific organismic limitations in a physiological sense. In the development and design of a teleoperator system, every attempt should be made to exploit human capabilities and to augment the limitations in much the same way as we deal with the machine components of the system.

Table 1-1: Capabilities and Limitations of Machine Systems

CAPABILITIES	LIMITATIONS
<u>Endurance</u> - Provided reliable machine components, machines will perform tasks around the clock	<u>Reliability</u> - Key component failure can result in greatly degraded performance or failure
<u>Exposure</u> - Can be hardened to withstand a very wide range of environmental parameters including pressure, temperature, radiation, forces, projectile toxics and similarly hostile characteristics	<u>Maintainability</u> - Servicing and repair requirements can preclude use of some machine components at remote locations
<u>Sensing</u> - Can be designed to detect a much wider range of energy than can humans, and the amount of energy for stimulation can be greatly lower while the amount tolerable can be greatly higher	<u>Reasoning</u> - Current programs and subroutines have not demonstrated that a machine can reason through a set of new problems or a set of new data
<u>Mobility</u> - Can move at faster rates, over longer distances, across more difficult tracts than can humans	<u>Predictability</u> - Machines can not recognize nor induce about unexpected stimuli or events
<u>Strength</u> - Can manage heavier tasks requiring prolonged exertion or high peak exertion	<u>Cost</u> - Very high costs are associated with machines which attempt to emulate human capabilities, or with very sophisticated and complex machines
<u>Channel Capacity</u> - Can be designed to attend to a large array of inputs from the environment, the command link or from other machines	<u>Flexibility</u> - In terms of operations, machines can perform only those operations for which they have been prepared
<u>Output Capacity</u> - Can be designed to carry out several tasks simultaneously	<u>Power</u> - Must have a continuous supply of operating power, usually electrical
<u>Calibration</u> - Can perform tasks with precision beyond human capability such as measurement, force exertion, signal selection	
<u>Repetition</u> - Can, within calibrated limits, perform repetitious tasks at very high rates without tiring or boredom	
<u>Information Processing</u> - Can process a vast amount of quantative information at very high rates	
<u>Speed</u> - Can perform tasks or gather information faster and slower than humans	

The specific considerations of human physiology and psychology are taken up in Section 6.0 of this document, but the general considerations can be summarized in the following table (Table 1-2). It can be noted that the general strengths and weaknesses of humans are complimentary to the weaknesses and strengths of machines.

Table 1-2: Capabilities and Limitations of Humans in Teleoperator Systems

CAPABILITIES	LIMITATIONS
Learning - Capable of modifying behavior to perform tasks	Recall - Reliability of recall of stored information is low
Integration - Capable of mixing several types of inputs into one integrated model	Sensory Inputs - Number of channels is limited and the amount of input is both selective and limited
Reasoning - Capable of inductive and deductive logic for problem solving and task performance	Endurance - Has a limited performance period depending upon task, after which performance degrades significantly.
Recognition - Able to recognize complex patterns viewed at new angles or in a very noisy background	Environmental Tolerance - Must be supported by appropriate chemical, biological, thermal and physical environmental conditions
Adaptability - Able to draw upon a wide range of information to solve new problems, and select alternative modes if certain modes fail to satisfy a problem	Speed and Consistency - Operate at generally slower speeds and with more variability than machines
Subjectivity - Able to make evaluations and estimations based on other than "factual" data	Strength - Limited muscular strength for mobility and manipulation
Serendipity - Capable of developing entirely new approaches and solutions	Fatigue, Stress, Attention and Motivation - Behavior subject to such variables which influence and consequently provide variability in performance

With this overview on operator/system considerations, we can move toward the development of teleoperator design criteria based upon the most appropriate combination of humans and machine skills and roles.

1.4 APPROACHES TAKEN TO COMBINE HUMAN/MACHINE ADVANTAGES AND OVERCOME THEIR LIMITATIONS

The allocation of roles and responsibilities between humans and machines in teleoperated systems is strongly influenced by the mission and functional objectives. Where the mission environment is well defined and the task functions are relatively simple and completely prescribed, it may be desirable to allocate a major portion of the tasks to machines which can be designed to accomplish the specified tasks. Where the remote site is not well defined and the tasks are of a wide ranging or general nature, it is more appropriate for the general problem solving capabilities of the human to be brought into the fore. Consequently, the first approach taken in allocating roles should be to thoroughly identify and describe the specific functional objectives; the capabilities of humans and machines can then be compared to each task within the functional objectives, and a preliminary assignment between the human and machine can be made. In those areas where the human operator has been given primary performance responsibility, the next step is to identify the system support characteristics such as scene feedback, flight command and control, manipulator control, and data gathering and analysis. Following the definition of this support, a training and mission simulation plan should be developed and implemented to ensure that the operator is fully capable and suitably trained to carry out the mission tasks.

Similarly, in areas where machine components of a teleoperator system have been assigned primary roles, an engineering assessment of hardware reliability, redundancy, software operations, environmental hardening and component compatibility needs to be made. Research into, and development of, advanced subsystems may be required, and development of system software is also required. System integration and checkout to ensure proper hardware and software operation are as essential to the machine components as training is for the human. At the same time, trade analyses should be conducted to affirm that the original assumptions of human and machine synergism are still valid for the particular mission model. Table 1-3 describes those steps which are necessary to accommodate the teleoperator mission requirements within human/machine constraints.

With the general system considerations in mind, we can move on to the specific considerations of human perception and remote system concepts as the two crucial components of teleoperators.

Table 1-3: Approaches to Define Roles of Teleoperator Components

Prepare Mission Description
- Mission Objectives
- Functional Objectives
- Task Descriptions

Categorize Candidate Tasks
- Detail of Definition - Well defined/amorphous
- Precision - Gross skills/high tolerance
- Repetition - Single task/multiple performance
- Information Requirements - Quantitative/qualitative
- Complexity - Simple, straightforward/multi-dimensional, convoluted
- Endurance - Short lived/long lived tasks

Assess State-of-the-Art
- Hardware Capabilities
- Software Capabilities
- Research and Development Requirements

Assignation of Roles
- Human - Assess capabilities and limitations
- Machine - Assess capabilities and limitations
- Trade Studies - Performance, reliability, economic criteria

System Integration and Checkout
- Training - Human
- Simulation - Hardware/software
- Operations Verification - Full teleoperator system.

2.0 REMOTE SYSTEM CONCEPTS

More variable in configuration and more amenable to design change than the human component of teleoperator systems are the remote system concepts. Regardless of configuration or application, each remote component of a teleoperator system shares most of the following characteristics:

1. Physically removed from the operator - Whether separated by a wall or some vast stretch of space, the two primary teleoperator components do not share the same space.

2. Under the command and control of the human operator - The primary mode of operation is human command via data link, and even for those tasks under local control, the human exercises supervisory control. This is the point that distinguishes teleoperators from robots—locus of control.

3. Sense the remote location - The operator's ability to perform remote tasks is influenced by remote feedback of the task environment; consequently, teleoperators are equipped with some sense systems such as manipulator force feedback and stereoscopic viewing.

4. Effect the remote site - The primary tasks proposed for teleoperators involve remote manipulation of some aspect of the remote location; additionally, mobility at the site is often provided for the remote system, both of which would have an effect on the remote site.

In the area of space based teleoperators, the most convenient method of defining remote systems concepts is operationally, that is, through their proposed areas of application or operation.

2.1 APPLICATIONS

For manipulation of payloads and carrying out remote duties around the Shuttle, the best known teleoperator is the Shuttle remote manipulator system (RMS). It is designed to be operated from the Shuttle aft flight deck through a control panel with TV and direct viewing feedback.

The operations it will perform are grappling payloads for deployment from the orbiter bay or retrieval of payload from space. It will assist extravehicular activity (EVA) crew members in maintenance and servicing activities and can support a work station from which EVA can be conducted.

In the area of mobility systems, the sophisticated planetary rovers and space probes used for remote sensing and sampling offer an excellent example of extending the human's investigatory interests into hostile and extremely remote environments. Some planetary rovers have also been equipped with manipulator arms for surface sampling and manipulation. But for sensing, mobility and manipulation, the proposed Shuttle-deployed free flying teleoperator represents the richest range of applications and operations. Some of the operations proposed for the free flyer are:

- o Payload deployment
- o Orbital retrieval
- o Stand off inspection
- o Surveillance
- o Servicing and repair
- o Module installation, removal and replacement
- o Rescue missions
- o Environmental sampling
- o Docking and capture
- o Assembly and construction
- o Fabrication.

If a system is designed in terms of the operations it performs, then advanced space teleoperators will have a very broad definition covering their many applications.

2.2 BASIC CONCEPT CONSIDERATIONS

The teleoperator subsystems are dealt with in detail in Sections 3.0, 4.0 and 5.0, but the following summary outlines some of the general considerations for remotely manned systems.

Mobility - Transportation to or about the remote site is provided by several classes of mobility systems. Gas jets for space travel, propulsive screws for water environments, tracks and wheels for terrestrial environments, propellers and wings for airborne vehicles. Other mobility system examples are surface effects systems, rail guides, air bearings, crawlers, and similarly special systems. The goal is to provide maneuverability at the remote site for task performance at numerous locations.

Sensory - In order for the human operator to fully understand and appreciate the remote site, it is necessary for the remote system to have on-board sensory instrumentation which can relay data to the operator. For local control, it is also desirable for the teleoperator to have a "sense" of itself. Forces, torques, pressure, speed, temperature, vision and acoustic information might be desirable for specific applications. The remote system can be designed to sense information beyond the range of the human and can transform this information for human interpretation.

Manipulative - General and special purpose manipulators can perform a wide range of effective tasks at the remote site, particularly with specialized end effectors such as tool attachments. The manipulators can resemble human arms or be made to accommodate special task conditions through non-anthropomorphic manipulators. The manipulators can be made longer, thinner, stronger, and more dexterous than human arms, or to most any specification required by the task.

Intelligence - While considerable electromechanical advantage can be obtained with the remote system through teleoperation, the state-of-the-art in artificial intelligence does not currently approach that of the human. While local programs for very specific tasks have been realized, it is recognized that the primary decision making tasks are allocated to the human. As research improves artificial intelligence, this balance will shift and we will move closer to autonomous remote systems. The major components of remote system concepts will have slight variation as function and environments change, and the details of space-based teleoperator components are discussed later.

3.0 VISUAL SYSTEMS

During the Teleoperator Technology Development Program, an extensive range of visual systems was investigated as well as the effects of those visual systems upon operator performance. This section provides results of the visual system investigations, including sensor and display systems, transmission and environmental parameters, and the role of the human operator in television feedback systems.

3.1 SENSOR SYSTEMS

Due to the availability and advanced technology incorporated into black and white television sensors, these primarily have been used in visual system testing. Vidicons, image intensifier orthicons, silicon intensifier vidicons, charged coupled devices (CCD), and charged induction devices (CID) provided scene sensing for black and white feedback.

As a test standard, a COHU model 2000-100 vidicon was utilized, with test results being compared in terms of operator performance using the COHU baseline system. Sensor systems used with the COHU include:

- General Electric TN 200 (188 horizontal lines)(Ref. 2)
- General Electric/MSFC CID prototype (188 lines)(Ref. 3)
- Sony DXC-5000 B color camera
- Westinghouse CCTV Series 1200
- General Electric Series 500 vidicon
- Sterotronics Stereocaptor sensor lens.

Each of these sensor systems was used with a special or general purpose CRT display to provide feedback to the operator.

3.2 DISPLAY SYSTEMS

The primary visual display system used in the evaluation was a CONRAC CNG-8 20 cm (7.75 in.), diagonally measured, black and white raster scan CRT display. The size and power rating of this display were judged to be compatible with most space flight missions, and similar displays are widely used in laboratory settings. The early (1971-1974) laboratory work on human perception was all done using this baseline system.

Additional displays evaluated in the visual system laboratory included:

- CONRAC monochrome CRT, model SNA9 (30 cm diagonal)
- Thomas 4M 27P-M monochrome CRTS (6.0 cm x 7.6 cm)
- Panasonic TN95 monochrome CRT (22.5 cm diagonal)
- Sony Trinitron DVM-1200 color monitor (30 cm diagonal).

The Thomas displays were incorporated in dual channel Fresnel displays for stereoscopic viewing. The first such display was the MSFC/Martin prototype Fresnel display, and a latter version was the flight configured Fresnel display (Ref. 4). Figure 3-1 shows the operational layout for both of these displays.

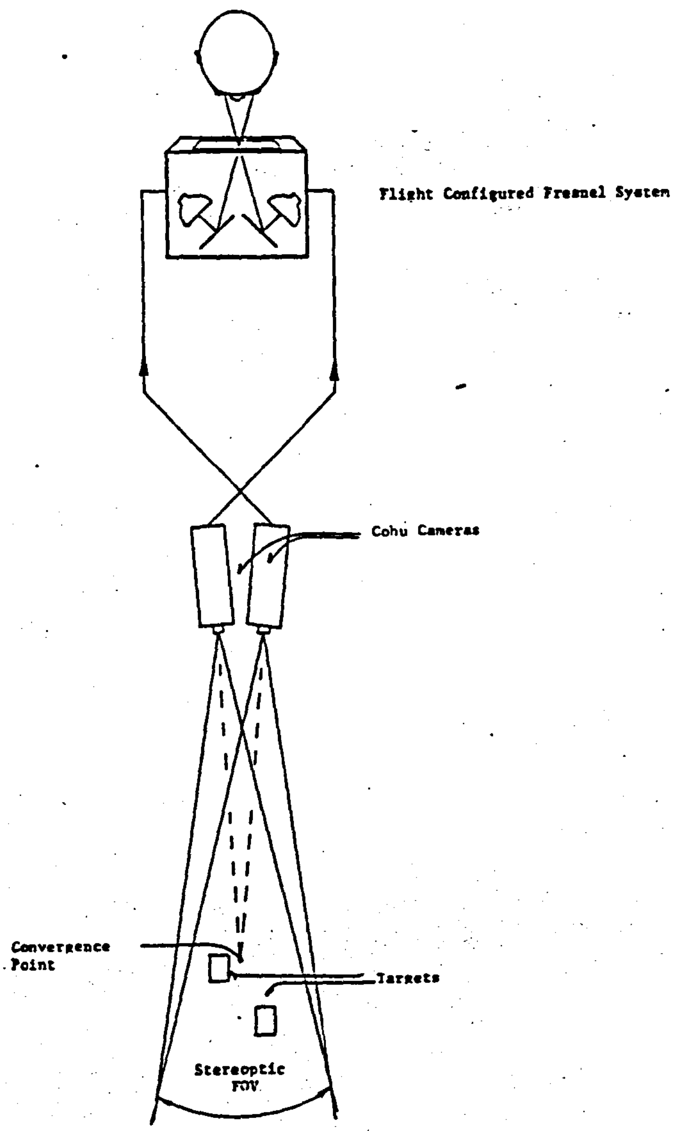


Figure 3-1: Flight Configured Fresnel Stereoscopic Display

The Panasonic display was used with a Honeywell stereo camera which provided stereoscopic viewing through electro-optical piezoelectric ceramic lead lantham zirconate titinate (PLZT) eye glasses. The PLZT glasses alternately presented the output of two cameras to the right and left eye of the observer at a rate above the critical flicker frequency (CFF), thereby permitting the observer to perceive a single, fused stereoscopic picture (Ref. 5). The operational layout of the PLZT display is shown in Figure 3-2. The Sony Trinitron was used during color discrimination testing, and the larger screen Conrac was used in studies to determine optimal CRT display size.

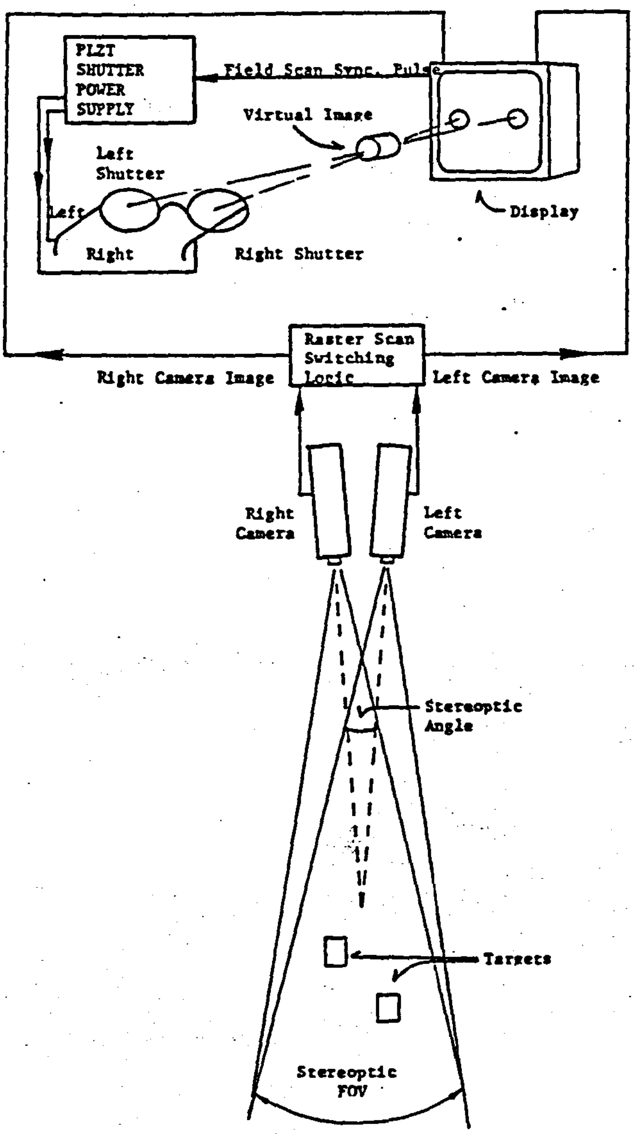


Figure 3-2: PLZT Stereoscopic Display

3.3 TRANSMISSION PARAMETERS

Intervening in the display and sensor link are factors of signal transmission such as power, bandwidth, frame rate, etc. In order to study the effects of transmission parameters on operator performance, the visual system laboratory incorporated the following components:

- A random RF noise generator, General Radio Corporation Type 1390-B, which provided signal-to-noise ratios of 15 dB, 21 dB and 32 dB

- An analog-to-digital, HS-615 A/D, and digital-to-analog, HS-2615 D/A, converter, from Computer Labs, which permitted transmitting a 4 bit digital signal

- A narrow band pass filter which allowed the televised signal to be broadcase at 1.0 MHz

- A video disc memory system, Data Disc, for selecting transmission frame rates of either 15 fps or 30 fps

- A variable field-of-view zoom lens, Cohu Model 2305, 20-80 mm.

A summary of transmission parameters studied under the Teleoperator Technology Development Program is presented in Table 3-1.

Table 3-1: Levels of Television System Parameters

Transmission Parameter	Levels Studied
Signal format	Analog 4 bit digital
Band width	4.5 MHz 1.0 MHz
Signal to noise ratios	15 dB 21 dB 32 dB
Field of View	10^{o} horizontal 25^{o} horizontal
Frame rate	15 frames per second 30 frames per second

3.4 ENVIRONMENTAL AND SYSTEM PARAMETERS

The visual system portrays to the operator the results, not only of sensors, transmission characteristics and displays, but the scene environment and the task object. Several considerations of these factors were taken, including target-to-background contrast ratio, scene illumination, target size and shape, target markings, operator visual aids, and viewing angles (Ref. 6).

Target background ratios could be varied from black on white to white on black in percent reflectance steps of .1. The equation for computing the contrast was:

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

where R = Reflectance
B = Background
T = Target.

The impact of target and background contrast has been shown to exert a very significant effect on human visual performance.

Scene illumination has been varied in the laboratories along a range from solar simulation (approximately 10,000 foot candles) to low light conditions of 20-30 foot candles. Illumination will effect target contrasts and sensor operational capabilities; consequently, scene illumination has been shown to be very important in visual performance.

Targets of varying sizes and shapes have been employed to determine minimum detectable targets and most accurately identifiable shapes. The addition of markings on the targets has also been investigated.

The number of visual scenes and the viewing angles of a task have been studied for systems using more than one monoscopic sensor and display. The effects of multi-camera angles and orientations have been particularly evident in placement and positioning tasks.

Other system parameters which have been studied concern the television resolution in terms of effective horizontal lines or pixels, operator visual aides such as dynamic or static cursors and reticles, and the inherent differences in stereoscopic and monoscopic viewing.

The effects of each of these parameters have been measured independently and in combination with one another. The measures have principally been in terms of the effects on human performance.

3.5 HUMAN OPERATOR PERFORMANCE MEASURES

Typically the human can perform tasks which can be measured in terms of accuracy or response time. These quantifiable terms are very useful for comparing similar tasks under different test conditions if the operator is fully familiar with the task at hand. Differences in task time or accuracy can then be attributed to differences imposed by the particular system being studied. For this reason, results reported here are most often described in terms of time to perform a given task (response latency) and how well that task was performed in terms of some predefined objective criteria (response accuracy). In most cases it was appropriate to use both time and accuracy as performance measures, so many of the test results are described by both measures.

3.6 PSYCHOPHYSICAL CONSIDERATIONS

Since the human is considered an integral part of any teleoperation system, those capabilities and limitations of the human which are discussed in Section 6.0 should be considered as primary system design criteria and treated as such during the design and development of teleoperators.

3.7 LABORATORY DESCRIPTION

The Visual System Evaluation Laboratory contains all test apparatus required for evaluation of visual systems proposed for use on the teleoperator vehicle. Historically, the potential video camera/monitor systems have been installed, tested, and modified in the visual lab prior to installation and further testing in the mobility or manipulator laboratories. Basic research has also been conducted to specify detailed design requirements for the teleoperator visual system.

The visual laboratory is set up in one large room divided into three distinct areas: (1) space for the subject and the display equipment, (2) the experiment control station, and (3) the test area, where the task scenes are set up for display to the subject.

The laboratory visual system allows a maximum of two video inputs from any two sources. For example, two black and white cameras or two color cameras are available for providing sensor inputs to the subject's display system. System inputs are selected and switched via two RCA T5-28, one-input, audio-follow switchers.

The laboratory equipment provides for the manipulation of any of the following parameters and shows those levels studied.

- Transmission: black and white and color (one gun)
- Camera/monitor configurations: 1 camera, 1 display; 2 cameras, 2 displays; 2 cameras, 1 display; and special effects generation
- Depth of view: monoscopic, stereoscopic
- Monitor sizes: 19.7 cm (7.75 in) diagonal, and 30.5 cm (12 in.) diagonal (standard)
- Field-of-view of camera: 8° to 35° horizontal

- Frame rate of display: 15 frames/sec.; 30 frames/sec.
- Signal format: analog; digital, 4 bit
- Signal to noise ratio: 32 dB, 21 dB, or 15 dB
- Viewing aids: electronically generated reticles and cursors; overlayed reticles; ranging radar
- Target motion: Fore-aft, variable translation rates; rotation, variable rates
- Variable target parameters: shape, size, brightness, 2- or 3-dimensional
- Variable target/background contrasts
- Variable target/camera geometries
- Variable scene lighting, special lighting sources.

Each of the several parameters can be combined to permit the study of system component interactions.

3.8 VISUAL SYSTEM RESULTS

- The visual angle required for shape recognition was found to be influenced by type or shape, highly angular shapes being recognized at smaller visual angles (Figure 3-3).
- Signal-to-noise ratios below 15 dB significantly degrade performance, while those above 21 dB do not exert such a negative influence (Figures 3-4 and 3-5).
- Detection of a gap between two targets requires an average of 4.15 arc minutes for detection.
- Generally, brightness discrimination between two targets is enhanced for contrast values of .25 or greater.
- Size discrimination between two targets is also strongly effected by target-background contrast, and contrast ratios of .6 should be employed for size discriminations.
- Recognition of shapes and patterns is strongly influenced by contrast, transmission format and signal-to-noise ratio, with high contrast, analog signals, and adequate S/N separation yielding the best recognition (Figure 3-6).

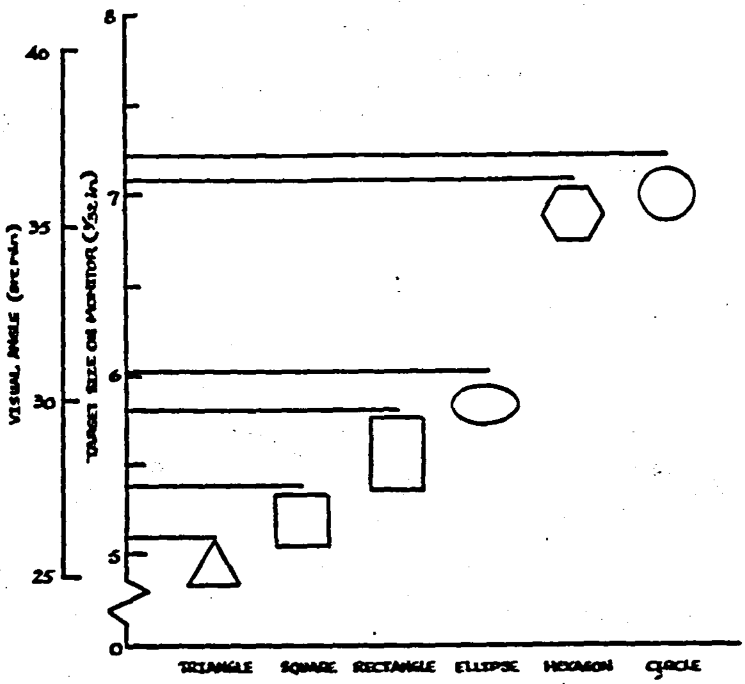


Figure 3-3: Target Size at Recognition as a Function of Shape

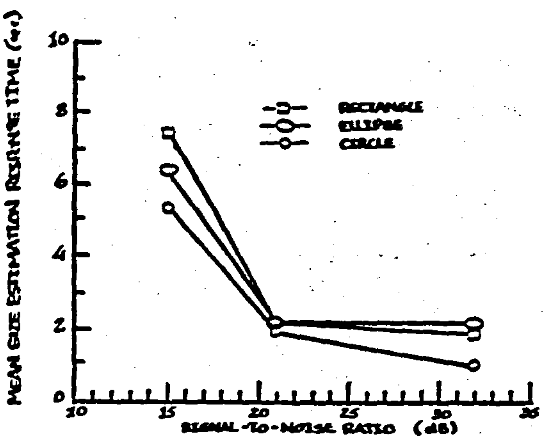


Figure 3-4: Mean Size Estimation Response Time as a Function of Figure Type and Signal-to-Noise Ratio (dB)

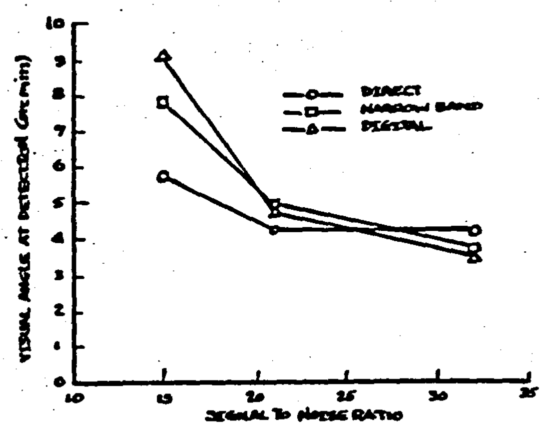


Figure 3-5: Mean Visual Angle in Arc Min at Detection as a Function of Transmission Mode and Signal-to-Noise Ratio (dB)

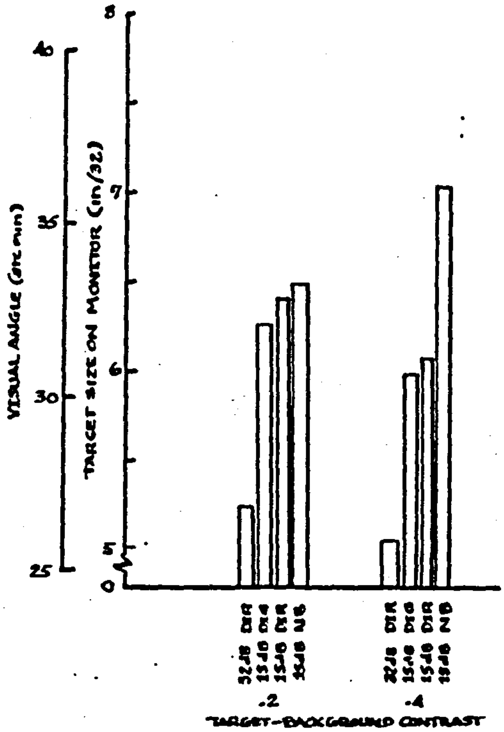


Figure 3-6: Target Size at Recognition as a Function of Target-Background Contrast, Transmission Mode and Signal-to-Noise Ratio (dB)

- o Judgments concerning fore-aft target separation are strongly influenced by camera configuration and camera type. Orthogonal monoptic camera pairs yield good results, while split field stereoscopic systems yield less accurate separation judgments.

- o Judgment of deviation from the horizontal or vertical plane is difficult to make for offsets of less than 3°, and this appears to be a threshold value for detection of angular deviation.

- o The dramatic interaction of camera line of sight, target alignment/offset and direction of target illumination was demonstrated when subjects failed to detect target misalignment of 10° when a solid target was inclined within 30° of the illumination source. The direction of misalignment could not be accurately judged for offsets of up to 35°when only the face of the target was illuminated.

- The mode of transmission affects visual performance. Digital transmission degrades visual acuity, as it does brightness discrimination where contrasts of .5 produced error rates of 10%. Size discrimination suffers a threefold increase in error for digital transmission relative to that of a direct 4.5 MHz mode. Narrow bandpass filtering of the transmission degrades visual acuity to a lesser extent.

- Color discrimination should be limited to 10-14 colors for maximum discriminability. The Munsell notations for these colors are:

No.	Hue		Value/Chroma	No.	Hue		Value/Chroma
i	2.5	R	4/14	viii	7.5	G	5/10
ii	8.75	R	MAX	ix	7.5	G	4/10
iii	6.25	YR	MAX	x	7.5	BG	4/8
iv	8.75	YR	MAX	xi	3.75	PB	4/12
v	2.5	Y	8/16	xii	10.0	P	5/12
vi	2.5	GY	7/12	xiii	10.0	P	4/12
vii	7.5	GY	6/12	xiv	5.0	RP	3/10.

- Recognition of alpha-numeric characters is influenced by character density, character contrast, viewing distance, and monitor size. Analog transmission of 4.5 MHz and 32 dB S/N will yield .99 probability of character recognition. When the character height subtends a visual angle of 30 arc min, the character width is 23 arc min and the stroke width is 5.5 arc min (futura demibold) (Figure 3-7).

- The probability of detecting target motion is increased as the absolute rate of change of the target diameter increases. Positive and negative rate changes can be detected at the 90% level at rates of .025 in/sec change in target diameter using reticle cue. For conditions without reticle cues, rates of .04 in/sec are required.

- The range estimation of targets is dependent upon target size, brightness, contrast and comparative aids such as reticles. Movable reticles tend to improve range estimation compared to fixed reticles over a wide variety of conditions (see Figures 3-8 and 3-9).

- Advanced stereoscopic TV systems, such as the Fresnel display, provide enhanced depth perception, especially when combined with an electrically generated depth cursor. However, the restrictions on lateral head movement imposed by Fresnel displays must be considered in control and display design.

- Gap resolution performance depends on signal-to-noise ratio and transmission mode. The visual angle required for detection with .90 probability ranges from five arc minutes for a 32 dB signal-to-noise ratio, regardless of transmission mode, to nearly 20 arc minutes for a digital transmission system with signal-to-noise ratio of 15 dB. The corresponding mean visual angles are 3.7 and 9.1 arc minutes.

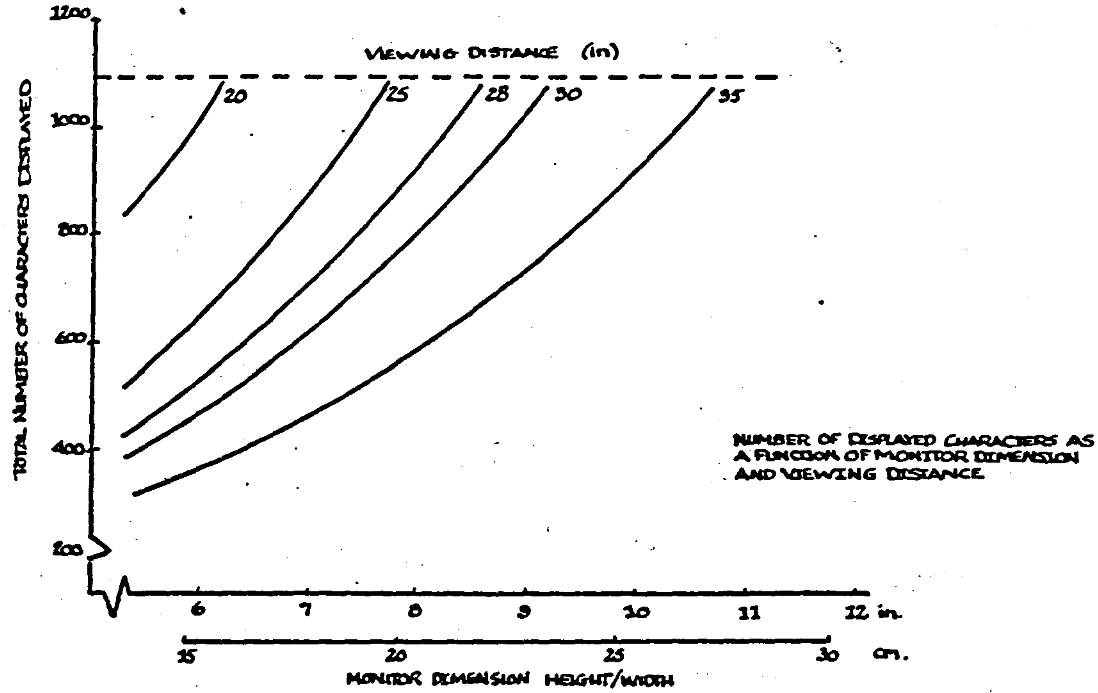


Figure 3-7: Number of Displayed Characters as a Function of Monitor Dimension and Viewing Distance

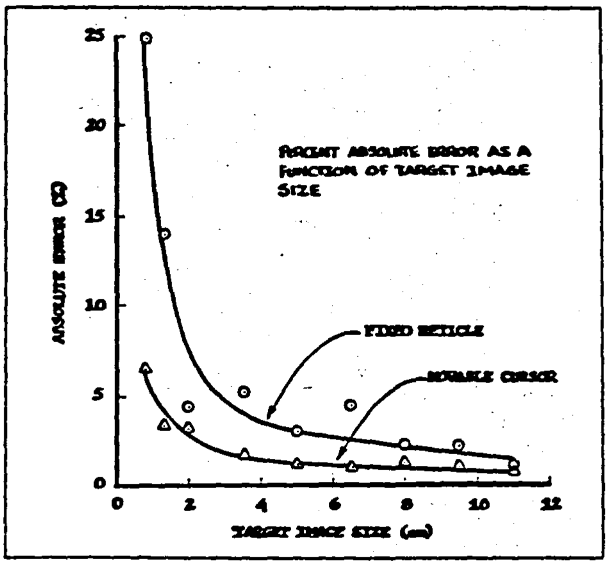


Figure 3-8: Percent Absolute Error as a Function of Target Image Size

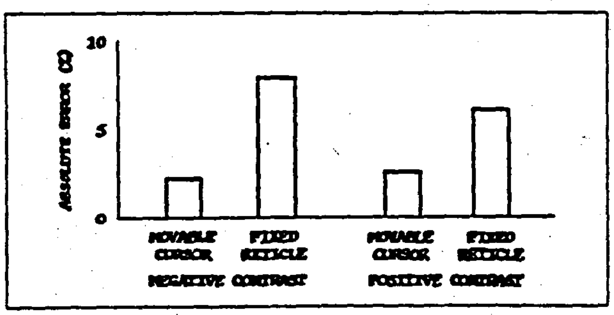


Figure 3-9: Percent Absolute Error as a Function of Cursor Type and Contrast

- o Brightness discrimination performance depends on transmission mode. With direct transmission, a contrast ratio of .20 produces near certain discrimination. With digital transmission, however, ratios as high as .25 to .50 yield error rates of 5% to 10%. The time required to judge brightness differences decreases to a minimum of about one second with contrast ratios above .25.

- o Recognition of familiar geometric shapes requires a mean visual angle of 25 to 40 arc minutes depending on the type of shape and transmission conditions. This represents an angle twice as large for TV viewing as for direct viewing--the accepted subtense for direct form recognition being 12 to 20 arc minutes.

- o Size discrimination performance depends on target-background contrast. With contrast ratios of .625, the linear dimension size discrimination threshold is on the order of ±.10. Reduced contrast of .125, however, raises the threshold value to ±.30 (see Figure 3-10).

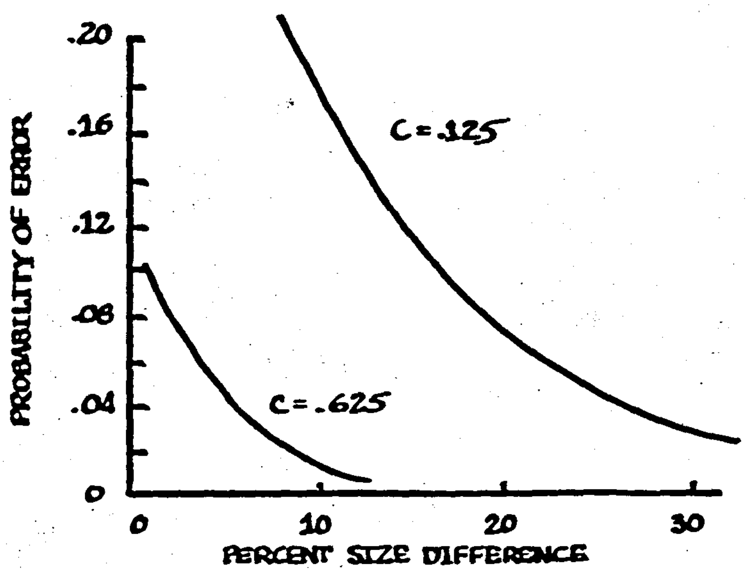


Figure 3-10: Effects of Contrast on Judgments of Target Size

- Estimation of single target size depends on target-background contrast and true target size. Percent absolute size estimation error ranges from 15% to 40% depending on the values of these variables.

- Estimation of target separation in the fore-aft direction depends on camera mode and true separation. Mean absolute estimation error expressed as a percentage of true separation varies from 10% to 30% depending on true size for an orthogonal monoptic viewing system to as much as 50% to 70% for a system using single camera stereoptic viewing in the target plane (Figure 3-11).

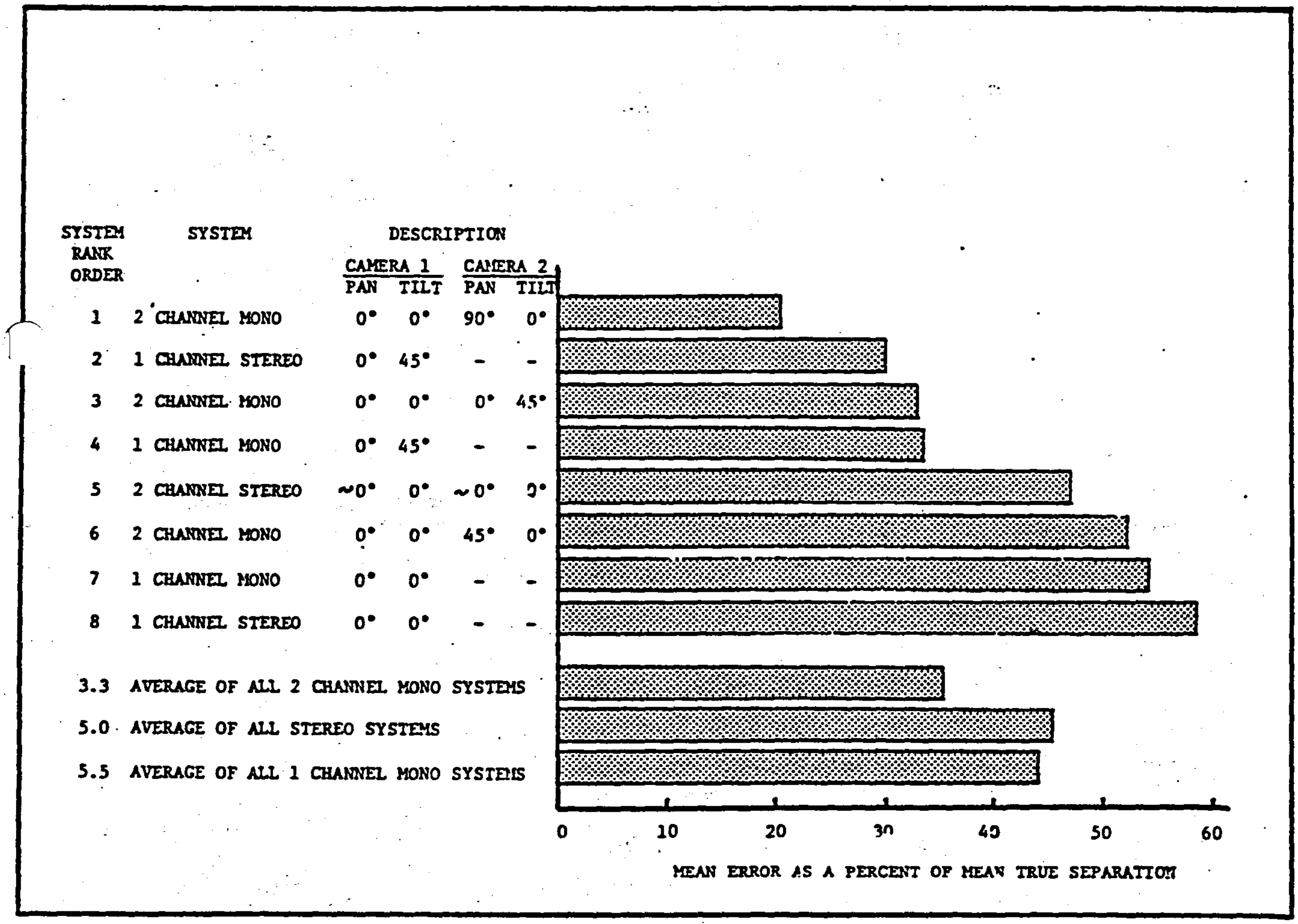


Figure 3-11: Performance Results of Judging Fore/Aft Separation of Two Targets as a Function of Video Systems

4.0 MANIPULATOR SYSTEMS

In order to perform dexterous tasks at a remote site, teleoperators can be outfitted with a wide range of specialized or general purpose manipulator systems. These systems generally are comprised of end effectors, manipulator arms, hand controllers and some mediating control scheme. The approach taken in the manipulator system evaluation laboratory has been to combine the various subsystems into alternate manipulator system configurations and exercise these systems against a standardized manipulator system evaluation criteria. This has permitted the development of relative figures-of-merit and comparisons of dissimilar systems on similar tasks.

4.1 MANIPULATOR ARMS

Manipulator arms which operate in a manner that resemble human arms are called anthropomorphic arms. Both anthropomorphic and non-anthropomorphic arms have been employed in teleoperator manipulator investigations. Further, manipulative tasks have been performed with single and bi-lateral manipulator arms. Table 4-1 presents an overview of arms which have been exercised in the Manipulator System Evaluation Laboratory.

Table 4-1: Manipulator Arm Subsystems

Manipulative Arm	No. of Arms	Configuration
Rancho Los Amigos	Two	Anthropomorphic
Ames Hardsuit	One	Anthropomorphic
Extendible Stiff Arm Manipulator (ESAM)	One	Non-Anthropomorphic
Advanced Dexterous Anthropomorphic Manipulator System (ADAMS)	Two	Anthropomorphic
Protoflight Manipulator Assembly (PFMA)	One	Non-Anthropomorphic

Each of these manipulator arms could be terminated with a working end effector for performance of teleoperated dexterous tasks.

4.2 MANIPULATOR END EFFECTORS

End effectors or dexterous terminal devices can generally be classed as special purpose or general purpose. Examples of specialized end effectors would be wire strippers, welding heads and socket wrenches. Generalized end effectors would be exemplified by the parallel or opposing jaw grippers. Table 4-2 summarizes the end effectors and terminal devices used in the system evaluations.

Table 4-2: End Effector Subsystems

Effector Name	Description
Dorrance Effector	Classic general purpose curved prosthetic hook with grasping accomplished by closing opposed jaws
Protoflight End Effector	An opposed jaw type, general purpose effector with adaptive grooves for clamping tools
Terminal Kit Adaptor (TKA)	A collection of special purpose tool heads which can be mounted in a terminal receptacle fitted to a manipulator arm. Tool heads include wire cutter/strippers, hexagonal head wrenches, pliers, socket wrenches, and padded opposing jaws
RMS End Effector Capture Device	A special purpose can-type with an internal snare for capturing docking probes
MSFC 3 Finger Grappler	A special purpose grappler end effector for securing a trailer hitch ball probe
Opposed Jaw	General purpose end effectors, of which several types were studied

There are several other end effectors which are available for study, notably the tactile/force sensing end effector which is equipped with proportional touch sensors in the jaw pads, the mechanically actuated trigger hand (MATH) for the grasping and triggered operations of standard power tools, and the attached optical array proximity sensor which permits sensing the near environment of the end effector prior to actual physical contact with the task elements.

4.3 HAND CONTROLLERS

There are two significant classes of hand controllers--integrated and discrete. In discrete controllers, each movement or operation of the manipulator is controlled by a single command input. Toggle switch controllers are of this type, where joint movement is directed by toggle movement. Integrated controllers, on the other hand, control the movement of several joints simultaneously to move the manipulator to a commanded position and orientation. While some discrete control modes were studied early in the teleoperator technology development program, most of the emphasis has been on the varieties of integrated controllers. Table 4-3 presents some pertinent information on manipulator hand controllers available for study in the laboratory.

4.4 CONTROL APPROACHES

Several control approaches are available for the management of manipulator operations, ranging from one-on-one toggle and joint controls to computer resolved manipulator tip position controls.

The methods followed in the manipulator laboratory have been to exercise several arms with several different types of hand controllers where the mediating control processes would permit. Some of these mediating control approaches have been based on rate control or proportional rate control wherein the amount of deflection in a hand controller was manifested in manipulator arm movement or proportional speed of movement. Some other control approaches have involved positional changes in the hand controllers with those positional changes reflected in the manipulator. Such is the case in the master slave arm control approach. Still other approaches have involved the mediation of inputs by computer software which resolve controller commands into appropriate arm motions to control the position of the end effector. This is an example of a terminal pointer control program.

There are other computer-assisted or computer-managed control approaches where subtasks or operations are automatically executed by preprogrammed subroutines. The initiation and supervision of these subroutines are always under the control of the human operator, unlike the autonomous functions inherent in robotics.

The manipulator systems and the individual subsystems have been tested in MSFC teleoperators since 1973. Since the possible combinations of end effectors, arms, hand controllers and control approaches would yield a massive test matrix, Essex has developed a hierarchially structured manipulator evaluation criteria to reduce the number of potential test combinations based on performance criteria.

4.5 MANIPULATOR EVALUATION CRITERIA

If a decision must be made as to the most appropriate manipulator system to use on four specific tasks, the most straightforward approach is to test the systems on those tasks and select the best based on performance. But if there are three types of hand controllers, two control approaches, four end effectors and two types of arms to choose from, then selection by testing

Table 4-3: Controller Subsystems

Controller Name	Degrees of Freedom	Control Type	Characteristics
MIT Isometric (SD-2)	6	Computer Resolved	No force feedback; no position feedback; suffers cross coupling effect
Lever Analog MSFC	6 + End Effector Open/Close	Electro-mechanical drive link	Offers position & rate control
Analog Joystick	6 + End Effector Open/Close + Telescoping Extension	Electro-mechanical link resolved rate	Partial replica control of ESAM
Terminal Pointer	5 + End Effector Open/Close	Computer resolved proportional rate	Provides spatial correspondence between operator's hand & end effector; controls tip position
MSI Isometric 544	6	Computer resolved proportional rate	Single hand control of 6 DOF
MSI Isometric	6 + Open/Close Jaw	Computer resolved position or rate control	Single hand control of 6 DOF
AMES Exoskeletal	6 + Open/Close End Effector	Electro-mechanical linkage	Exoskeletal full arm and hand controller
ADAMS Master/Slave	6	Electro-mechanical linkage	Exoskeletal replica controller

becomes very difficult and expensive. The following equation gives some idea of magnitude of the problem:

4 (tasks) x 3 (hand controllers) x 2 (control approaches)
x 4 (end effectors) x 2 (arm types) = 192 trials

just to compare each possibility with every other combination. Usually more than one comparison would be required; five to ten trials is not unreasonable, so the evaluation is magnified by that factor. One means of reducing the experimental workload is to eliminate from further consideration those subsystem combinations which fail to meet performance criteria for simple tasks on the assumption that they will not be able to perform more complex (multi-degrees-of-freedom) tasks.

The manipulator evaluation criteria were designed to accomplish this progressive order. Details of the evaluation criteria are found in Ref. 7, but Figure 4-1 shows the general flow moving from simple positioning tasks to explicit system tasks such as module replacement. Performance criteria were generally task time and task accuracy, with system combinations which were utterly unable to perform a task set being eliminated from further consideration.

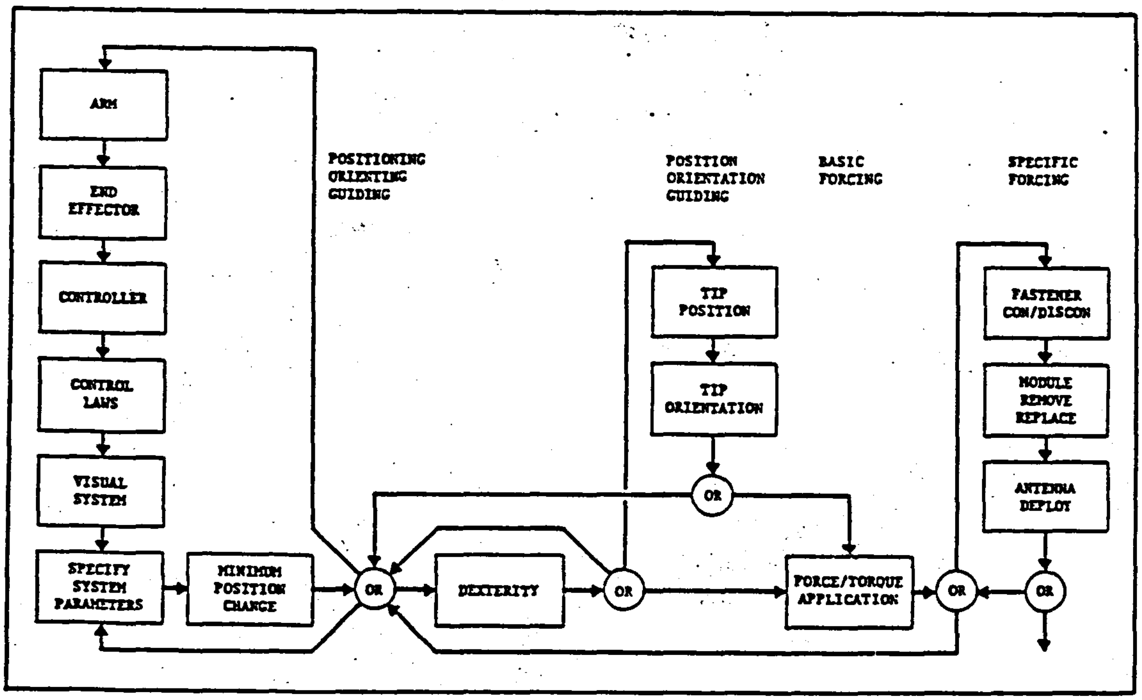


Figure 4-1: Flow of Manipulator System Tests

4.6 LABORATORY DESCRIPTION

The Manipulator System Evaluation Laboratory provides the laboratory space and testing hardware necessary to collect quantitative data on manipulator systems. The primary elements of the laboratory are:

- o A manipulator arm with associated hand controller(s), computer electronic subsystems, and visual systems
- o A task board to simulate typical servicing or assembly tasks
- o A remote operator's station that provides all controls and displays necessary to operate the manipulator and visual systems
- o An experimenter's station that provides the controls necessary to conduct the tests and the displays necessary to record performance data.

A manipulator room contains the manipulator arms under evaluation along with support equipment (lights, cameras, power supplies and task boards). The experimenter is stationed near the manipulator so direct visual observations of any arm may be made. A task board is positioned in the room near the appropriate arm. Task scene feedback is accomplished through the stereoscopic or monoscopic video system.

The operator's control room contains the operator's station, from which communications between the experimenter and operator are maintained via headsets. This isolation minimizes auditory feedback from the manipulator operations. At the station, the manipulator hand controller is placed in front of the operator, below the video monitors (Figure 4-2). Ambient lighting is provided by a diffused overhead flourescent lighting.

The third room, located between the control room and the manipulator room, houses a SEL 840A computer. It is through this computer that the selected controller outputs are transformed into manipulator commands.

For scene feedback the stereo camera video system consists of the following individual components:

- o Two TV cameras, Cohu Model 2006-011
- o Two telephoto zoom lenses, Canon Camera Company, Inc., Model TV 10x25, 16.5-95 mm, 1:2
- o One tripod, Hercules, Inc., Model 5454, for camera height adjustment
- o Two camera remote control panels, Cohu Electonics, Inc.

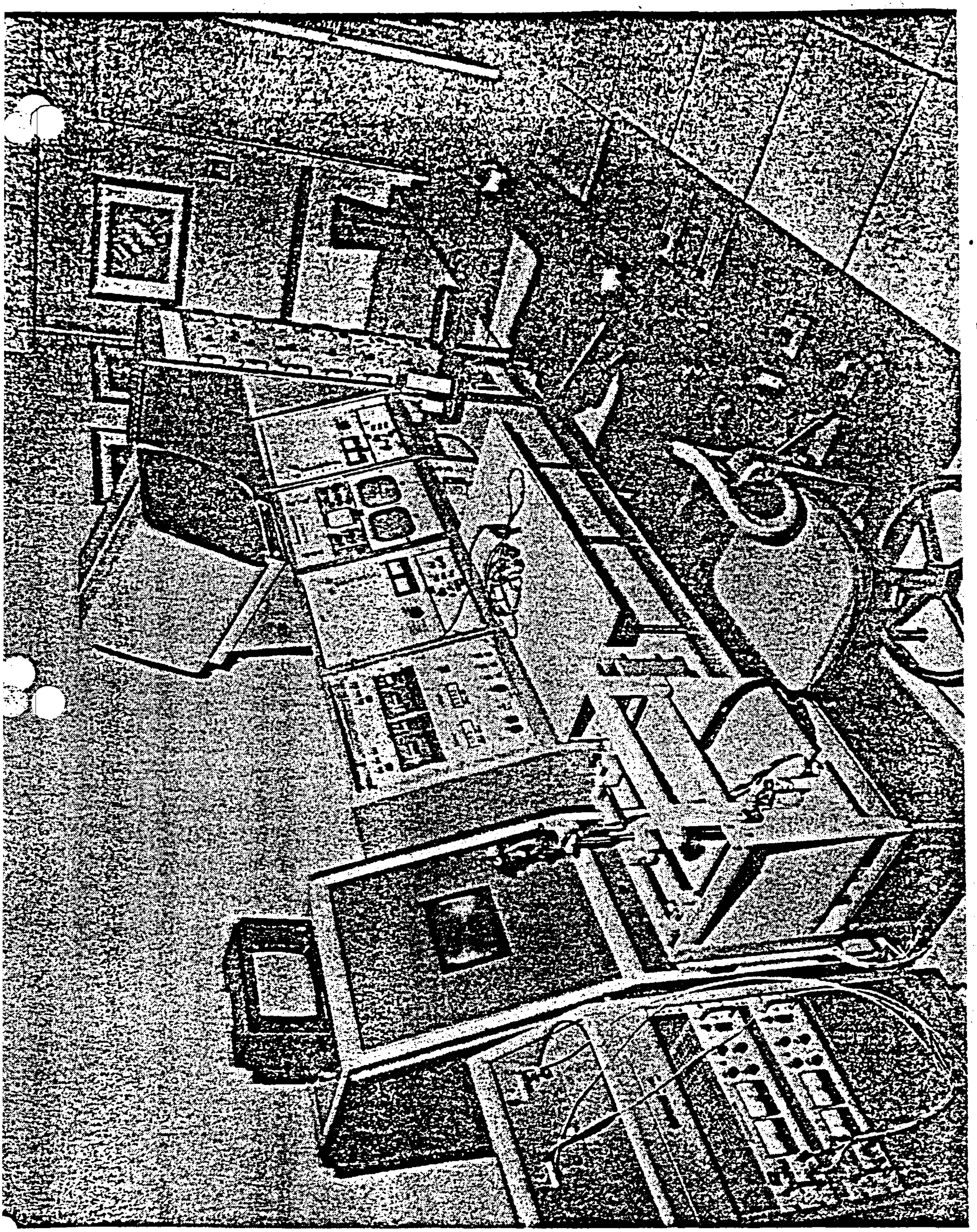


Figure 4-2: Operator's Station with Analog Controller and Stereo Setup

The distance between the two cameras (the camera baseline) is 12.7 cm (5 in). The iris, zoom, and focus functions are preset for the testing program, and their levels are verified between test runs. All ranges and convergence point distances are measured from a point equidistant from the baseline of the stereo camera pair.

Each video system generates a 525-line analog signal at 4.5 MHz at the Conrac monitors. The signal-to-noise ratio is 32 dB.

4.7 MANIPULATOR SYSTEM RESULTS

- Manipulator arms must be appropriately matched to the hand controller by degrees-of-freedom, operating correspondence and task requirements, and freedom from cross coupling in order to maximize system performance. Figure 4-3 shows the significant differences in two manipulator systems, one inappropriately matched by components.

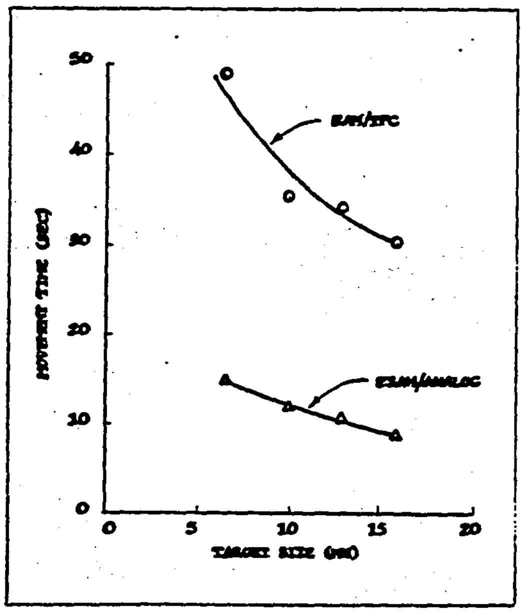


Figure 4-3: Movement Time as a Function of Manipulator System and Target Size

o Movements of the manipulator tip require more time for accurate terminal positioning and more time for large movements based on the equation:

$$\text{Index of Difficulty} = \text{Log}_2 \frac{2(\text{amplitude of movement})}{\text{terminal target diameter.}}$$

Figures 4-4 and 4-5 illustrate the effect of target size and movement on response time.

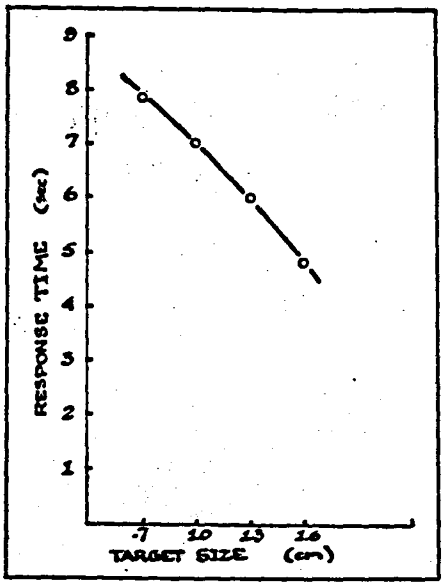


Figure 4-4: Effect of Target Size on Response Time

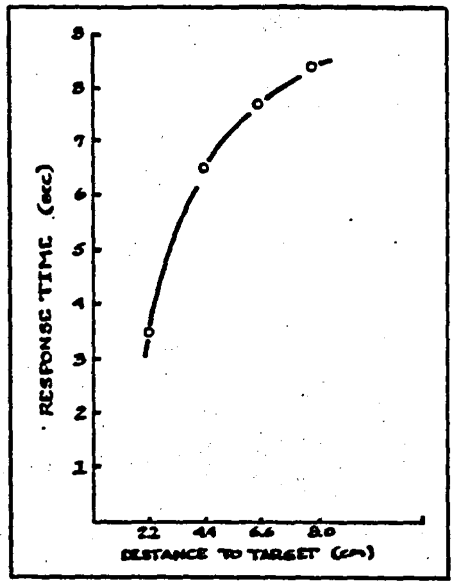


Figure 4-5: Effect of Target Location on Response Time

- Integrated hand controllers of up to 6 DOF have better demonstrated performance when freedom from spurious movement is reduced by adding friction to the controller joints or by reducing the gain in the controller. This provides some reduction in cross coupling effects, and reduced task time as well as increased positioning accuracy (Figure 4-6).

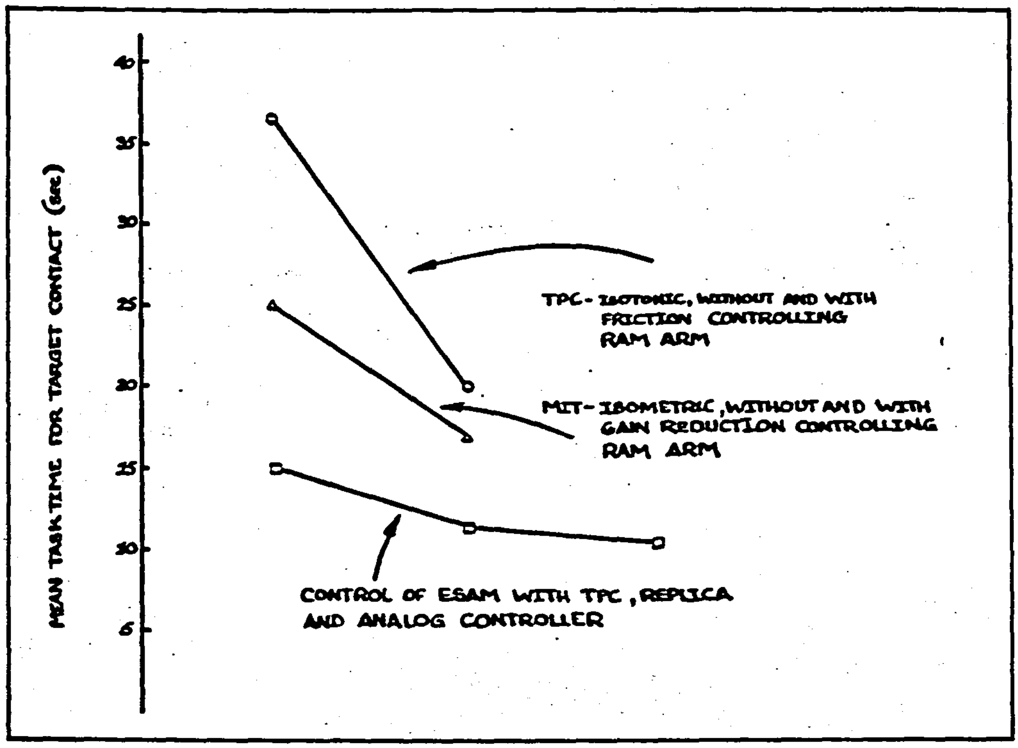


Figure 4-6: Time for Target Contact by Manipulator System Without and With Gains Reduced

- The direction of movement has been shown to have a significant effect on task performance time, but is largely dependent upon the type of controller and manipulator arm being employed (Figures 4-7 and 4-8).

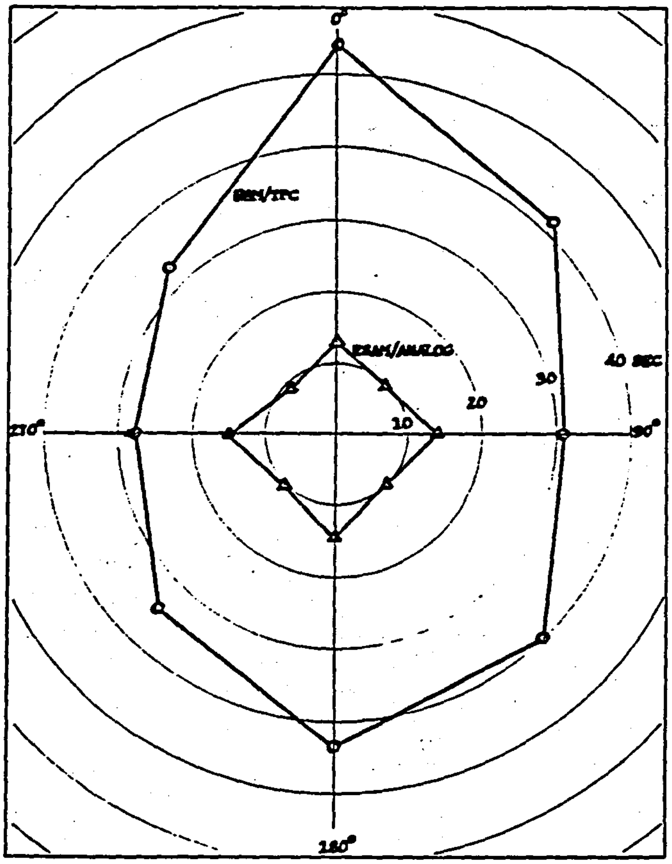


Figure 4-7: Mean Movement Time as a Function of Motion Direction and Manipulator System

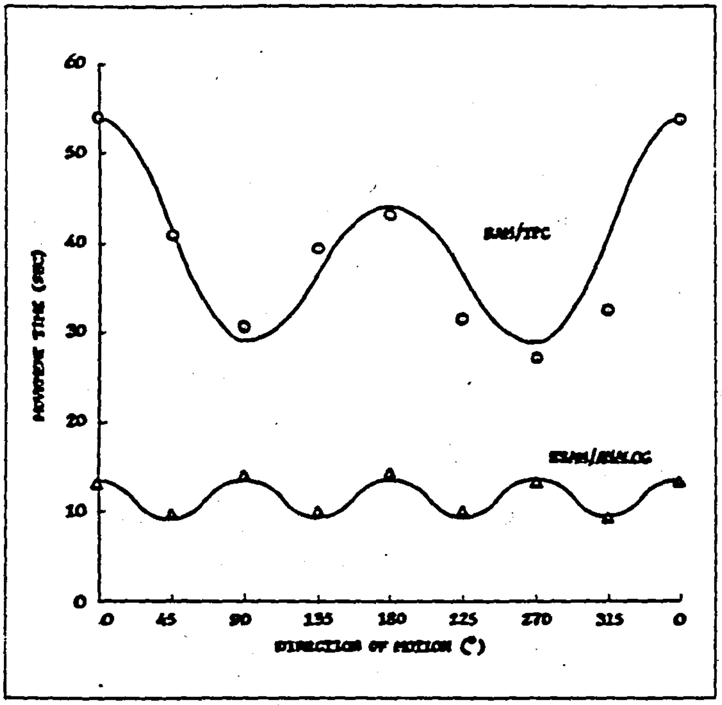


Figure 4-8: Movement Time as a Function of Manipulator System and Movement Direction

- The time to perform insertion and removal tasks is slightly increased for conditions where the task is offset in yaw with respect to the camera/manipulator line-of-sight.

- The time to insert and remove pegs decreases as the pegs increase in diameter. This conforms to Fitt's law and the Index of Difficulty Equation.

- Isometric controllers appear to offer some control advantages over isotonic controllers provided that the effects of cross coupling have been minimized in integrated controllers.

- o Work place layout and task arrangement should be carefully organized for tasks involving manipulator use. This is based on the findings which show increased time to perform offset tasks and tasks located along particular vectors.

- o The application of split controllers--those with attitude and translation incorporated in separate controls--should be limited to systems which apply to only one manipulator unit. The application of two manipulator arms will necessitate an integrated controller for each.

- o The evaluations of manipulator systems--controllers, arms, end effectors, feedback devices and control programs--should be accomplished through a standardized and hierarchical evaluation program which begins with simple, minimal degree-of-freedom tasks and proceeds through complex and mission-specific tasks. This provides for the early elimination of systems which fail to meet operational criteria of a manipulative task.

5.0 MOBILITY SYSTEMS

The means to rendezvous with, fly around, inspect, dock or capture a satellite or similar object will be provided by some manner of teleoperator mobility system. While the mobility system will vary with particular applications and environments (e.g., remote underwater work), the space applications will require a teleoperator propulsion system made up of on-board thrusters and thruster command and control logic, and remote flight station where the operator will control the teleoperator mobility (Ref. 8).

5.1 CONTROLLERS FOR VEHICLE MOBILITY

Consideration is given first to the flight station and the operations and equipment for remotely controlling teleoperator mobility. We have discussed the visual system for task and environment feedback, and we have discussed the hand controllers for manipulative exercises. Along with these two major subsystems will be flight controllers for maneuvering the teleoperator. Two significantly different approaches can be taken in designing the flight controllers. The first is to have the manipulator hand controllers serve a dual function as 6 DOF flight controllers, and the second is to have dedicated flight controllers. The advantage of the first approach is in the controlling hardware—only one set of hand controllers is required. Its disadvantage is that the vehicle mobility and manipulative systems cannot be exercised at the same time, but the assumption is that one would not manipulate until securely docked, precluding the co-operational mode. The advantage of the second approach is that there are two distinct subsystems for mobility and manipulation control, and any particular differences between the two subsystems can be reflected in the controllers. This would certainly be the case if a replica or master slave hand controller was used for manipulation. The disadvantage stems from potential hardware redundancy and space constraints at the flight station. These are considerations for tradeoffs and not absolute criteria.

The effort to date in the mobility laboratory has centered around dedicated mobility control, and where necessary, dedicated docking or manipulator control. The laboratory has employed a single 5 DOF joystick—the Z axis is not currently active on the mobility flight simulator but will be in the near future—for control of teleoperator attitude and translation, and a two-stick control system with attitude and translation divided between the two control sticks. Either controller scheme imparts command information to the on-board propulsion units via RF link. The propulsion control can be varied through the logic of the hand controllers.

5.2 PROPULSION CONTROL MODES

Regardless of which controllers are used, they can transmit selected firing information to the on-board thrusters. The logic for this information is modifiable in the following ways:

1. Displace stick and transmit thruster firing information for as long as stick is displaced. This is termed CONSTANT THRUST MODE.

2. Displace stick and transmit discrete thrust information, that is, one thruster firing for each displacement of the stick. This is termed DISCRETE THRUST MODE.

3. Displace stick and transmit information which causes the thrusters to fire at preset intervals for as long as the stick is displaced. This is called TRAINED PULSE THRUST MODE.

None of these thrust modes is proportional, that is, related to the amount of stick displacement, although this type of proportional control is possible in the laboratory. While variable propulsion control is available through the hand control logic, it is also available through the on-board thrusters.

5.3 THRUSTER MODES

The current mobility unit employs 16 thrusters which are each calibrated at one pound of thrust. The thrusters are attached to the mobility unit in groups of two at each of eight corners as shown in Figure 5-1, with the operational schematic shown in Figure 5-2.

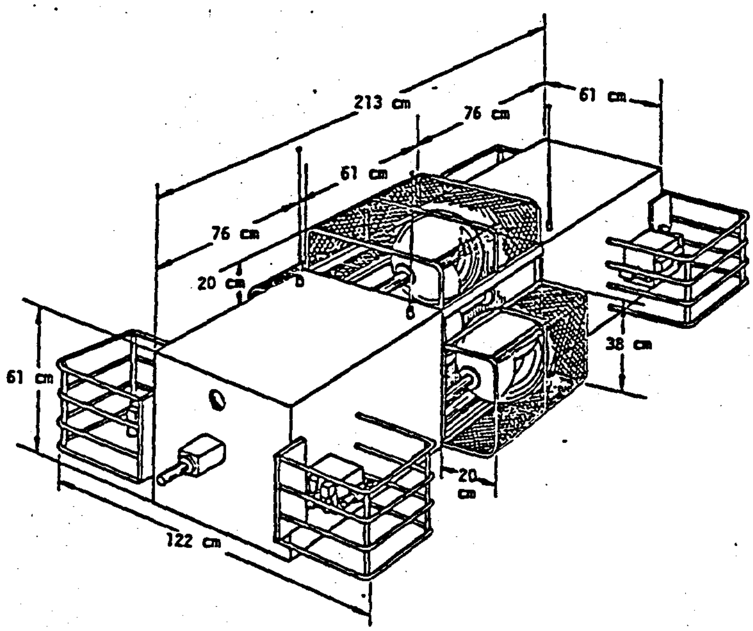


Figure 5-1: Mobility Unit Physical Dimensions and Thruster Configuration

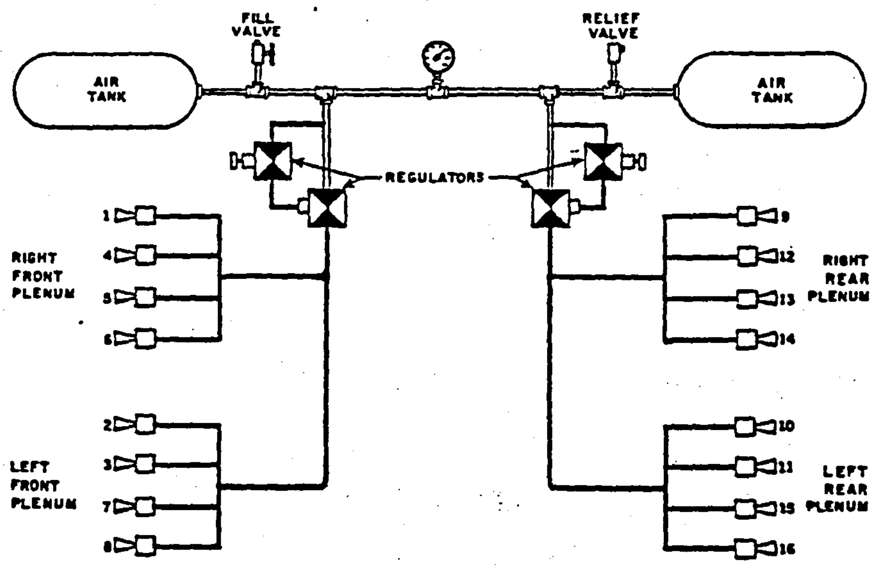


Figure 5-2: Compressed Air Propulsion System and Thruster Arrangement

5.4 LABORATORY DESCRIPTION

The Mobility Systems Evaluation Laboratory at MSFC has been used to evaluate command and control systems and docking hardware since 1974. The free floating mobility unit (MU) and associated control hardware were designed to simulate a small, unmanned, remotely controlled space vehicle operating in a near proximity rendezvous and docking situation. This capability has been extremely useful for the evaluation of teleoperator equipment such as crew hand controllers, camera positions, video displays, and docking probes. Crew procedures and equipment operating characteristics have also been evaluated.

The mobility laboratory is located in the high bay area of Building 4705 at MSFC and contains a 111 m^2 (1200 ft^2) flat floor, a free floating MU, and an operator control room.

The flat floor is a poured, black epoxy surface (type Moran 109-B-71). It is basically circular with a diameter of 11.6 m (38 ft) and is enclosed in a 12.2x12.2x6.1 m (40x40x20 ft) test area of black, light absorbing curtains. The epoxy, poured to a depth of 3.3 cm (1.3 in), forms a precision surface with less than 0.02 cm variation measured over 125 separate locations. Air conditioning is provided to maintain a constant temperature and to minimize the accumulation of dust on the test surface floor.

The test area is illuminated by four banks of two-1250 watt quartz iodide lamps suspended from the ceiling in the enclosure corners and angled to converge the greatest illumination near the center of the floor. Additionally, a Spectrolab Night Sun, SX/16, search light is installed in the test facility to serve as a source of simulated solar illumination. The light unit is a zenon plasma arc lamp that generates a peak beam of 20 million candlepower from an input of 28 Vdc at 65 amps. The lamp is mounted 3.2 m (10.5 ft) above the laboratory's air bearing flat floor on a remotely controlled pan and tilt unit for target tracking.

Adjacent to the test area is the operator's test console which is enclosed in a 9.0 m^2 (95 ft^2) sound-insulated room. The test console contains much of the same type of equipment that may be used in the Shuttle aft cabin control station for the control of teleoperated activities.

5.5 TEST EQUIPMENT DESCRIPTION

The free flying MU has five degrees-of-freedom with modifications currently underway to incorporate ±Z as the sixth degree-of-freedom (Figure 5-1, above).

The nominal crew command/control input devices are two (3 DOF each) spring-loaded, center-return, 7 cm (2.75 in) control sticks (Micro-Avionics, P/N MA-65-2AT). Displacement of the left-hand controller corresponds to translation movements of the MU. Displacement of the right-hand controller results in attitude movements.

The command subsystem has nine subcarrier frequencies operating on nine 450 MHz range carrier frequencies which have the capability to be excited two at a time. This yields a potential of 36 command signals. The command signals are generated at the operator's console via a hand controller. The hand controller, when displaced, closes a set of relays which transmits binary signals to the MU, initiating thruster firings.

The MU propulsion system uses compressed air operated through four groups of four thrusters each that provide pure moment and axial thrust. The propulsion system command thruster logic is presented in Table 5-1. Figure 5-2 (above) shows the major system elements.

Table 5-1: Thruster Command Logic

Thruster Command	Thruster Response
Forward	14, 14
Aft	6, 7
Right	8, 16
Left	5, 13
Yaw Left	5, 16
Yaw Right	5, 13

The air bearing system consists of three 30.5 cm (12 in) circular pads, pressure regulated at 2.4×10^5 N/m^2 (35 psi) to float the vehicle with a .05 mm (.002 in) clearance. The total volume of compressed air stored in the lower bay of the vehicle is .073 m^3 (2.604 ft^3) at a pressure of 10.3×10^6 N/m^2 (1500 psi).

The lower bay houses the compressed air supply, contains the air pads, and supports the upper bay. It also serves as a mounting support for the air bearing pedestal upon which the MU is free to roll and pitch about a center point. This lower bay is 48.3 cm high and 116.8 cm in diameter (19x46 in) and is painted a non-reflective flat black to minimize the operator's visual cues.

The propulsion system of the MU, as mentioned earlier, serves the dual purpose of vehicle translation and attitude control. Each group of four thrusters is clustered about the longitudinal axis of the vehicle (one group at each corner). Each thruster is controlled by a solenoid valve at the thrust chamber injector and was measured at approximately 4.45 N (1 lb) thrust for 4.12×10^4 N/m^2 (60 psi) plenum pressure and a 100 msec. pulse duration. Total volume of compressed air for the upper bay of the vehicle is 0.074 m^3 (2.6 ft^3) at a rated pressure of 10.3×10^6 N/m^2 (1500 psi).

The unfueled mass of the MU is 752.4 kg (1262 lb) of which 419 kg (923 lb) is the top bay. Fueling the MU added 18.46 kg (40.7 lb) to the total mass. However, half of this was used for the air bearing pads, leaving 9.2 kg for use by the propulsion system.

5.6 MOBILITY SYSTEM RESULTS

- Rendezvous and docking tasks with large mass targets--those of a mass greater than the teleoperator--required 135 seconds and 150 psi of fuel to accomplish a hard dock between the two vehicles. Docking with low mass targets required 227 seconds and 214 Δ psi of fuel due to the ability of the teleoperator to "push" the low mass target around.

- The differences in constant thrust and trained pulse (5.5 pulses/sec) were significant for fuel expended during a docking task (228 Δ psi for constant thrust and 138 Δ psi for trained pulse), and the trained pulse also demonstrated a slight advantage in time to dock--193 sec vs. 169 sec.

- This difference was demonstrated in standoff approach and docking tasks with the trained pulse mode yielding mean times for approach and dock of 210 sec versus 302 sec for constant thrust. While not a statistically significant variation, it does tend to support the results of other thrust mode studies. The same trend was apparent in the use of fuel with the pulsed thrust mode requiring 30% less fuel than the constant thrust mode.

- In controlling a two vehicle docking task, the time and fuel consumption differences between a one-hand integrated controller and two-handed attitude and translation controllers were slight, and the apparent advantage mixed:

  Single hand controller - 193 sec. and 177 Δ psi
  Dual hand controller - 169 sec. and 188 Δ psi.

- When controlling a docking probe on a low mass vehicle, some more apparent advantages to the single hand controller are demonstrated. The probe was an extendible/retractable lock type probe which fitted into a ring capture device rather than a conical drogue. The time and fuel expended to dock for a single and dual hand controller system were:

  Single hand controller - 80.8 sec. and 58.75 Δ psi
  Dual hand controller - 112.6 sec. and 60.0 Δ psi.

- Current mobility studies have not demonstrated a significant difference between center mounted (bore sighted) camera systems, and off center (top mounted) cameras aimed at a docking target. The mean time to close from 6 m and dock using a bore sighted camera was 98.75 sec, while the mean time for an off-center camera was 94.3 sec. Mean fuel expenditure for boresighted trials was 81.5 Δ psi, and 85.0 Δ psi for off center camera trials.

- During docking tasks, the operator should be provided with scene lighting for illuminating shadowed docking probes and should also have manual control of sensor iris and target sensitivity so that image blooming of highly illuminated surfaces can be compensated for at the display. Automated sensors have tended to obscure targets of interest which may be in highly illuminated or deeply shadowed areas due to their "averaging" the task scene lighting conditions.

- In comparison of trained pulse, constant thrust and a single pulse mode over target offset conditions of ±45° misalignment, the trained pulse mode continues to exhibit an advantage in performance time:

  For trained pulse - 166.2 sec
  For constant thrust - 181.8 sec
  For single pulse - 451.8 sec

  while the single pulse mode demonstrates the worst performance for docking tasks.

- Figures 5-3 through 5-8 show typical performance results from a test series regarding target offset and target mass.

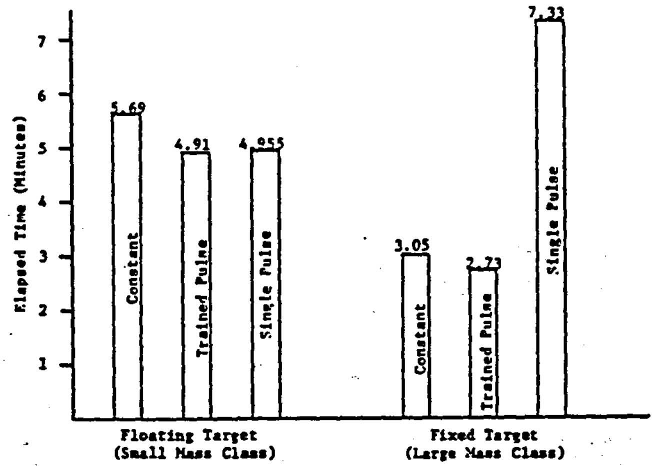


Figure 5-3: Elapsed Time as a Function of Thrust Mode and Target Mass

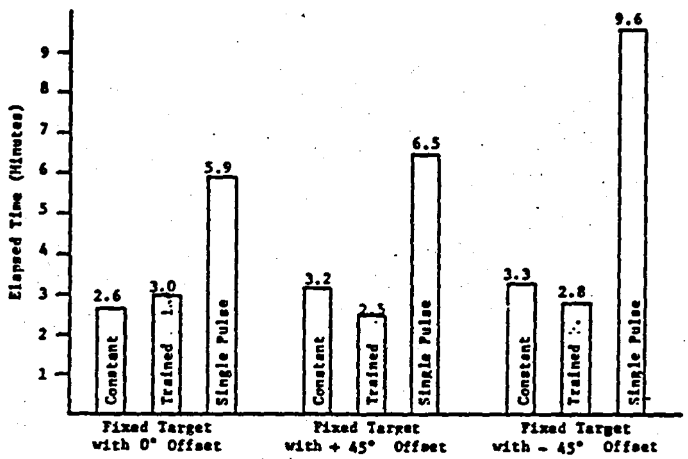


Figure 5-4: Elapsed Time as a Function of Thrust Mode and Target
Initial Starting Position (Large Mass)

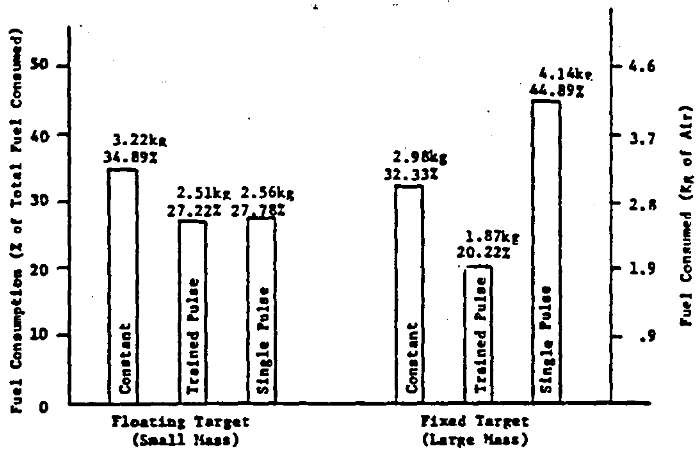


Figure 5-5: Fuel Consumed as a Function of Thrust Mode by Target Mass

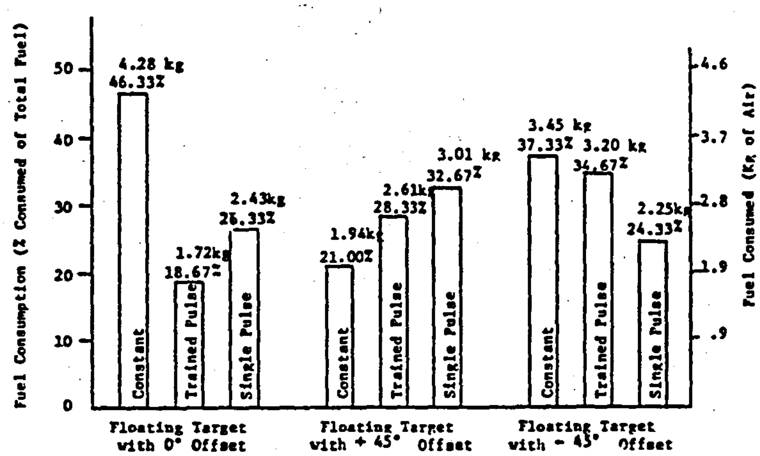


Figure 5-6: Fuel Consumed as a Function of Thrust Mode and Target Initial Starting Position (Small Mass)

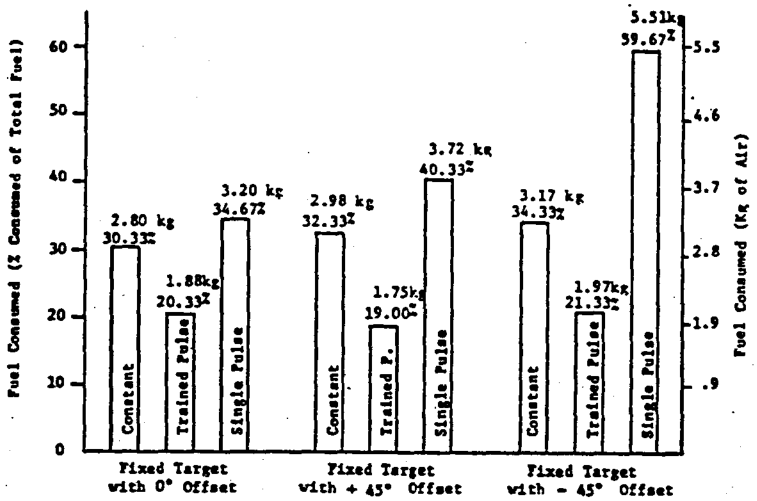


Figure 5-7: Fuel Consumed as a Function of Thrust Mode and Target Initial Starting Position (Large Mass)

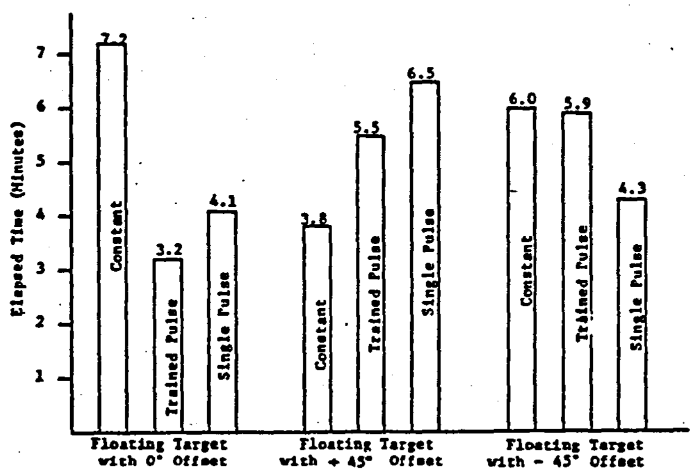


Figure 5-8: Elapsed Time as a Function of Thrust Mode and Target Initial Starting Position (Small Mass)

6.0 HUMAN PERCEPTION

The human senses play a critical role in our ability to manage our daily activities. Sight, smell, hearing, touch, taste, temperature, and balance are some of the sensations on which we rely as we move about our world. How we sense, as well as what we sense, are significant considerations in the design of complex human controlled remote systems. Understanding this enables us to take advantage of the inherent capabilities of the human perceptual system while augmenting it where necessary for the appropriate control of tele-operated activities. This section deals with the apprehension, processing and behavioral consequences of environmental energy impinging on the human.

6.1 SENSATION, PERCEPTION AND ENERGY

We sense our surroundings by evaluating several forms of energy in the environment—chemical energy for taste, wave motion energy for sound, physical pressure for touch, thermal energy for hot and cold, and electromagnetic energy for sight. We are surrounded by sources and reflectors of energy, and when it is in a specific range and an appropriate format for human sensory receptors, we speak of sensation. How we process this energy causes some profound changes in the original energy, and we impose on the sensation some learned interpretations. This processing and modification of sensed energy is called perception and is transcribed as "red," "loud," "cold," "bitter," and simple sensation. The perception of energy is not described in purely physical or quantifiable terms which can be attributed to the original sensed energy, but rather in subjective terms. This well noted human attribute of taking account of all of this stimulation, integrating it and deriving assumptions and "knowledge" about the world can be a most powerful component in teleoperator systems, since the control of the system is derived from the human (Ref. 9).

6.1.1 <u>Vision</u>

Seeing is our sensory evaluation of that portion of the electromagnetic energy spectrum from approximately 400 nanometers to approximately 800 nanometers. Radiated or reflected energy within that range which reaches the eyes is converted and passed to the brain, giving rise to vision, and some of the energy and vision characteristics are shown in Table 6-1. Since vision is considered a critical feedback mode for controlling remote systems, a short discussion of vision is in order.

6.1.1.1 Detection, Recognition, Discrimination and Scaling

Detection, recognition, discrimination and scaling are the concerns of the field of perceptual psychology called psychophysics. Psychophysics attempts to determine the relationship between the sensation registered in the brain and the physical stimulus that gave rise to it.

Table 6-1: Selected Characteristics of Human Vision (from Woodson, 1981)

PARAMETERS	VISION
Sufficient stimulus	Light-radiated electromagnetic energy in the visible spectrum
Absolute threshold of seeing	0.000001 ftL
Spectral range	Wavelengths from 400 to 700/Mµ (violet to red)
Spectral resolution	120 to 160 steps in wavelength (hue) varying from 1 to 20/Mµ
Dynamic range	~ 90 dB (useful range) for rods = 0.00001 to 0.004 mL; cones = 0.004 mL to 10,000 mL
Amplitude resolution	Contrast = $\Delta I/I$ = 0.015
Response rate for successive stimuli	~ 0.1 s
Reaction time for simple muscular movement	~ 0.22 s
Best operating range	500 to 600/Mµ (green-yellow) 10 to 200 fc
Indications for use	1. Spatial orientation required 2. Spatial scanning or search required 3. Simultaneous comparisons 4. Multidimensional material presented 5. High ambient noise levels

Detection - The initial function of the sensory system is to detect the presence of energy in the environment. Detection is the magnitude of a given stimulus (relative to a zero energy level) that is necessary for an individual to determine that something has been sensed. This minimal amount of energy is the "absolute threshold," and for the eye it has been determined to be one-millionth of a ft. lambert (Ref. 6).

The probability of visually detecting an object is a function of variables such as visual angle, contrast, luminance, etc. However, size seems to be the primary determinant if all other variables are held constant. Usually it is determined for a 50% probability of detection. In most cases it is desirable to design for a much higher probability value, such as 95%-99% thresholds so that targets will have a high probability of being detected. To obtain the size of target that will be detected of this probability, 50% thresholds should be doubled (Ref. 11).

Data indicate that the absolute threshold is not entirely "absolute," in that it seems to vary from measurement to measurement, or moment to moment. Part of the explanation lies in the fact that any stimulus must be detected through a fluctuating background noise. As the noise level changes, so does the threshold.

Several methods of investigation were developed in order to examine and further explain this phenomena. Of these, signal detection theory is the most developed. It is a mathematical, theoretical system which recognizes that the observer is not simply a passive receiver of stimuli but is also engaged in a process of deciding whether or not he is confident enough to say a stimulus is present. Thus, an observer's expectations, training and motives affect behavior and judgment as profoundly as actual stimulus reception.

Recognition - The recognition or identification of a specific stimulus out of a number of possible alternatives is another major task of the perceptual system. The difficulty of this task depends upon the number of possible stimulus alternatives and variables related to visual acuity. The degree to which the observer's identification of the stimulus corresponds to the actual stimulus input depends upon the ability of the sensory system to handle the input without distortion as well as the complexity of the input.

There is a hierarchical relationship between detection and recognition. Recognition requires that more stimulus information be available than for simple detection. The number of bits of information that can be perfectly recognized along a single continuum is approximately 7 ± 2, depending on the continuum addressed (a bit being defined as $\log_2 n$, where n is the number of stimulus alternatives). Also, the greater the number of stimulus dimensions, the better the recognition. Thus, many investigators have placed more emphasis on the quality or kind of information and the characteristics of the processor, and less emphasis on the quantity of information available.

Discrimination - As opposed to detection and recognition, discrimination focuses upon the question of the amount of disparity which must exist between two stimuli in order for them to be judged as being different. In a discrimination task, an observer must decide whether a signal came from one of two or more distributions along the same dimension, as compared to a detection task where a stimulus must be ascertained as coming from a signal or a noise distribution.

The same considerations of signal detection theory must be applied in the context of discrimination, however. The accuracy of discrimination is a function of several physical parameters of the stimuli which relate to a visual acuity. Also, there are decisional components present, such as expectations and motivations, that strongly influence an observer's perceptions. If a time critical response to a choice discimination task is required, it is important to remember that reaction time is related to the discriminability of the stimuli and the amount of information they contain. Discrimination times increase as the number of response alternatives increase.

Scaling - Scaling involves the subjective judgment of magnitude. This may address a stimulus magnitude, a sensation magnitude, or the magnitude of a complex psychological variable such as similarity or pleasantness. All sensory modalities obviously cannot be scaled along the same dimensions. Some perceptual experiences have an underlying aspect of intensity (e.g., brightness) while others do not (e.g., color). Psychologically, there is no quantitative difference between two colors; although they differ in wavelength, they just appear to be different.

Contextual effects seem to substantially influence judgments of sensory magnitude in many tasks. In an attempt to accommodate a dynamic and changing environment, an observer establishes a reference level against which all other stimuli are judged. All judgments are relative; a stimulus is weak or intense, near or far, only when judged against the subjective adaptation level.

The adaptation level consists of three classes of reference stimuli. First, there are the focal stimuli that are the center of attention, or those which are to be judged. Next, these are the background stimuli which provide the immediate background against which a focal stimulus is judged. Finally, there is the residual of stimuli the observer has experienced in the past (Ref. 12).

Visual Acuity - A fundamental physiologically-based function of the eye is its ability to resolve details or its degree of visual acuity. Visual acuity is a function of several variables, i.e., visual angle, brightness, contrast, image size and color. Acuity tasks are really forms of brightness discrimination since details to be resolved are basically defined by brightness differences in a strong relationship between visual acuity and the distribution of rods and cones on the retina. Since there are more cones in the central area, the fovea is the site of greatest acuity. The range of clear vision extends less than 10° away from the foveal center (Ref. 12).

The visual angle, or the angle subtended at the eye by the viewed object, is usually expressed in arc minutes. The formula for this value is as follows:

$$\text{visual angle (min)} = \frac{(57.3)(60)L}{D}$$

where L = the size of the object measured perpendicular to the line of sight and D = the distance from the eye to the object. The 57.3 and 60 are constants for angles less than 600 min (Ref. 13).

The amount of contrast in the visual field is a factor having a strong relationship to visual acuity. Contrast is the measure of luminance (measured in Lamberts) difference between a target and its background. It can be computed by this formula:

$$\text{contrast } (\%) = 100 \times \frac{L_b - L_t}{L_b}$$

where L_t = luminance of the target and L_b = luminance of the background; reflectance can also be substituted for luminance (Ref. 6).

As the ratio of minimum perceptible brightness differences (a measure of visual acuity) to field brightness increases, the visual contrast sensitivity of the cones (for daylight vision) remains relatively constant and the sensitivity of the rods (for night vision) decreases sharply. Assuming maximum contrast between a line and its background, at the lowest intensity of light, the eye can see a line whose width subtends a visual angle of 10 minutes. At very high intensities, the eye can see a line subtending a visual angle of less than 1 second.

There is an indirect relationship between contrast and image size. Given a "parallel bar" target at 30 mL brightness level, as contrast is increased, minimum size and spacing between bars can be decreased without obscuring the separation. With decreasing contrast, however, target size and separation must be increased to maintain threshold acuity, as follows (Ref. 10):

Contrast, %	45	8	5	3	2.8
Visual angle, min	1	2	4	10	16

Visual acuity also varies with different spectral illuminants as a function of brightness. When background brightness is 0.075 fc, the following values are found (Ref. 10):

Visual acuity, %	52	70	75	68	63
Wavelength (M)	485	520	590	625	665

When higher illumination levels are available, the relationship between illuminant color and acuity for black-and-white viewing is negligible. Factors such as luminance contrast, color contrast and exposure time are more important to acuity (Ref. 10).

The following graph (Figure 6-1) describes the relationship between the three critical variables which determine whether a person sees an object. As can be seen, it is desirable to maintain different brightness relationships between the primary visual task and immediate and distant visual phenomena.

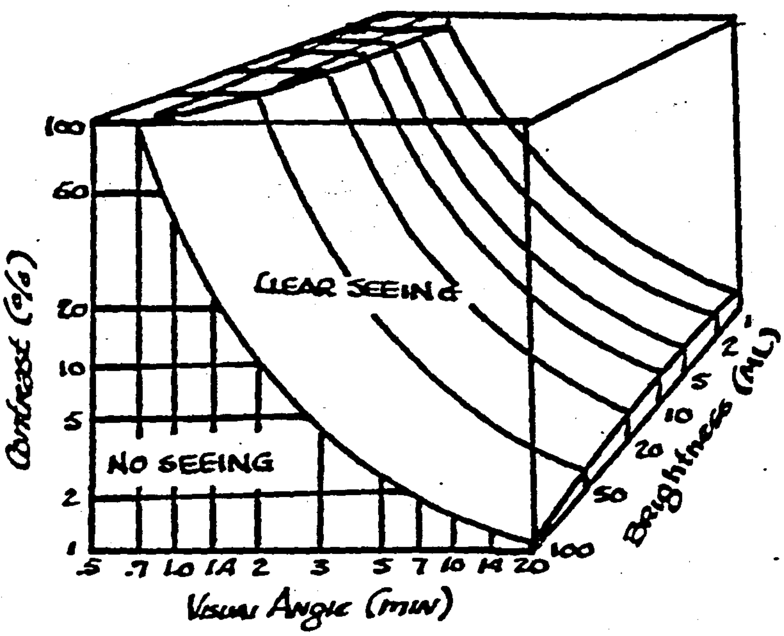


Figure 6-1: Relationship Among Contrast, Visual Angle and Brightness as a Determinant of Seeing (Woodson, 1981)

6.1.1.2 Color Vision

Color provides an important stimulus dimension that aids in the localization and identification of objects. The mechanism of color vision involves the reception of wavelengths or mixes of wavelengths of light energy by the cones of the retina.

Color consists of three attributes—hue, brightness and saturation. While some observers are capable of discriminating over 150 hues, the average person can accurately and reliably label only eight or nine hues. Color recognition depends on several factors, i.e., the color of the light source, the color of the reflecting surface or surfaces, and the state of the observer's visual system. Pale colors are more easily influenced by the color of the light being reflected by nearby surfaces. They are highly influenced by the level of illumination as well as the inherent reflectivity characteristics of the surface viewed (Ref. 10).

The utility of color as a redundant or augmentative code has extensive empirical documentation. It provides the observer with information in addition to brightness and contrast to aid in detection, recognition and discrimination tasks. For example, the application of color to a teleoperator visual system would greatly enhance inspection and servicing tasks. It would facilitate the operator's ability to detect damaged components and to distinguish between parts which have been color coded.

6.1.1.3 Depth, Distance and Speed

The process of space perception involves a number of different orientations. Egocentric localization refers to the sense of where one's body is in relation to other objects in the external environment. Object-relative localization involves the perception of the distance between objects in the environment. The last orientation is the comprehension of whether an object is flat (two-dimensional) or solid (three-dimensional).

The basic information processed by the brain to determine depth and distance can be explained in terms of "cues." Pictorial or monoscopic cues are those which require only one eye to register. They derive from geometrical considerations, and from the fact that light does not bend around a solid object. Cues which serve as the basis for monoscopic depth include: interposition or overlay, size, perspective, texture gradient, height in the plane, light (brightness), and motion.

Other cues for depth and distance arise from the physiology or structure of the visual system. These cues include: accommodation, information obtained from the pattern of muscle tension needed to change the shape of the eye's lens in order to focus objects at different distances; convergence, rotation of the eyes inward to focus the image of a close object on the fovea; divergence, outward rotation of the eyes in order to bifocally fixate a distant object; and, binocular disparity, the reception of different images on the retinas as a result of the horizontal separation of the eyes (Ref. 11). See Table 6-2 for further explanation of these cues.

Although the human eye has extraordinary capacities for seeing small details in faint amounts of light, it is very poor at estimating absolute values. For instance, the size of an unfamiliar target cannot be estimated accurately unless its distance is known. If distance must also be estimated, the estimate distortion will distort the corresponding size estimate even further.

Distances to targets are usually underestimated in an empty visual field, i.e., other objects that provide distance cues are absent. If the distance or size of another object is known, the distance to a target can usually be estimated with some accuracy. For example, it is nearly impossible to estimate the distance of a target seen against a clear background unless it is

Table 6-2: External and Internal Cues to Depth and Distance (Woodson, 1981)

	EXTERNAL CUES
Linear Perspective	Apparent convergence of parallel lines & related effects
Apparent Size	A strong cue to distance of objects of known size & texture
Motion Parallax	Relative angular motion as either head or objects move
Interposition	Nearer objects eclipse more distant ones
Aerial perspective	Contrast and color loss due to aerosols; useless in free space
Shading	A cue to three-dimensional form of objects (not to distance)
Apparent Intensity	A cue only to distance of effective "point sources"
	INTERNAL CUES
Accommodation	Relatively unimportant
Convergence	Useful limit is about 20 m
Binocular Disparity	Most important intrinsic cue to depth and distance

Note: All cues except for the last two can be utilized by a single eye, and by extension, in uniocular optical devices.

close or its size is known. <u>This will exhibit a profound effect during teleoperator approach and docking maneuvers if additional range and rate data are not available</u>.

Estimates of the speed of moving objects are also poor and are probably related to estimates of distance and target size. Little is known at this time about the human ability to estimate speed changes (acceleration) except that it is inaccurate and unreliable (Ref. 6).

6.1.1.4 Critical Flicker (Fusion) Frequency

The update, or refresh, rate on a TV monitor often causes the scene to "blink" or flicker. A visual phenomenon which is important to consider in this regard is the critical flicker (fusion) frequency (CFF). As an observer views a flickering light, it will eventually appear to be a steady, continuous light as the flicker rate is increased. <u>Thus, the TV update rate should be fast enough to reach this frequency, ~30 Hz</u> (Ref. 11).

A flickering light that is on 50% of the time and off 50% of the time and flashes at the rate of 10 Hz will appear brighter than a steady light. The following graph illustrates the relationship between CFF and target-area size. The smaller objects (2° to 0.3°) stimulate only the cones, where the larger areas (6° and 19°) yield a higher CFF due to the functioning of both rods and cones. The curves cross due to a shift from rod to cone vision (Ref. 10).

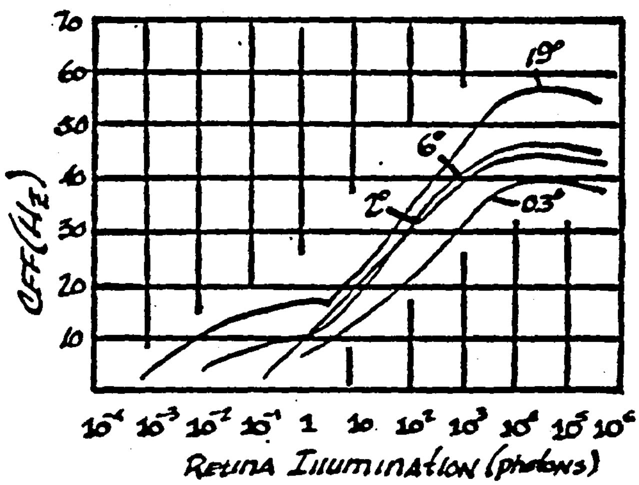


Figure 6-2: Target Size Retinal Illumination and Critical Fusion Frequency Necessary to Perceive a Continuous Light (Woodson, 1981)

2.1.1.5 Gestalt Phenomena

Gestalt is a German word for "form" or "whole." Gestalt psychologists were interested in the perceptual processes which caused certain elements of a visual pattern to seem to be part of the same figure or grouping while other elements belonged to other figures or groups. The basic tenet of the Gestaltists is that organization is part of any perception and not something added when elements are sensed. Humans tend to organize perceived flux in a way which holds changes and differences to a minimum while maintaining unity and wholeness. An entertaining example of this is shown in Figure 6-3.

Most basic in this process is a tendency to perceive a figure against a background. Compared to the ground, the figure will appear to: have shape, be nearer, be object-like, be more vivid, be more substantial in color, own the common contour between them, and have the ground extend behind it Ref.14).

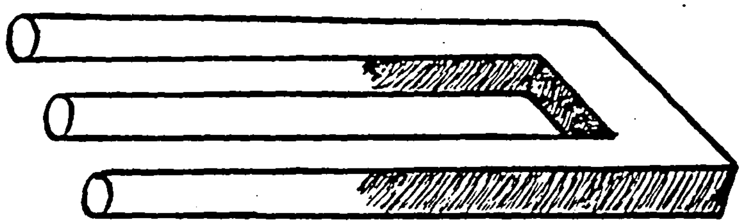
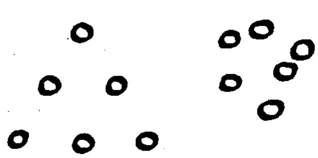


Figure 6-3: Perceptual Organization Imposed on a Nonsense Object

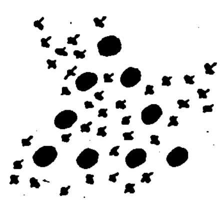
Several laws of perceptual organization were formulated which explain the perception of a figure. The Law of Proximity states that elements close to one another tend to be seen as a perceptual unit or figure. The Law of Similarity maintains that similar objects tend to be grouped together. The principle of Good Continuation holds that elements that appear to follow in the same direction tend to be grouped together. The principle of Closure maintains that when a space is enclosed by a contour it tends to be perceived as a figure.

The Gestaltists maintained that the principles of figural organization work together to result in the perception of the most stable, consistent and simple forms possible from the visual array. The perceptual system strives for regularity, symmetry and simplicity in order to reduce perceptual ambiguity (Ref. 11).

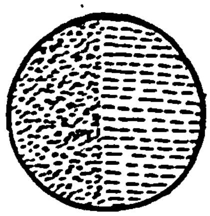
The following examples (Figure 6-4) illustrate the percepts of Gestalt phenomena. They help distinguish one of the differences between what is perceived versus what is reality (Ref. 11).



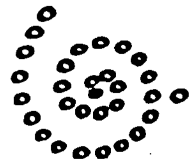
Proximity - Two clusters of dots, not 12 elements



Similarity - Triangle of dots on background of x's

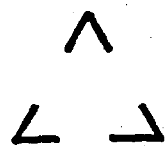


Similarity - The two halves appear very separate.



Good Continuation - Spiral of dots with one standing out.

Closure - Diamond between two lines, not a "W" or "M."



Closure - A triangle, not 3 acute angles.

Figure 6-4: Examples of Gestalt Phenomena

6.1.2 Proprioception

Kinesthetic and vestibular senses are two somatic, or bodily, senses which closely interact to maintain balance and provide information about the internal state of joints and muscles and about gravity. They jointly account for the human's ability to perceive (1) the position and orientation of the body and limbs, (2) the movement of the body and limbs, (3) the position or attitude of vehicles with a human in the vehicle, and (4) the movement of vehicles with a human in the vehicle. These senses take on added importance in the absence of, or with reduced, visual information. There are times, however, when they provide erroneous information and may conflict with visual information.

6.1.2.1 Kinesthetic and Vestibular Senses

The kinesthetic, or muscle, sense provides information on the position of the limbs, how far they moved, and the general posture of the body. It also provides information about changes in orientation and equilibrium. This is accomplished by detecting reflex changes in the muscle system which maintains posture, or by detecting changes in the position of body members as caused by external forces. Under these circumstances, the stimuli provide information only that some change has occurred; visual cues must be correlated to determine the exact nature of the change. The unique characteristic of the kinesthetic sense is that its stimulation originates within the body itself, as opposed to external stimulation.

The major function of the vestibular system is to help maintain an upright posture in the 1-G environment and control eye position as the head is moved while viewing various stimuli. This is accomplished by little "weights" found in the organs of the inner ear. Due to inertia, they tend to be stationary when the fluid in the semicircular canal is displaced in response to changes in linear and angular velocity.

The absolute threshold for perception of motion by the vestibular sense is between 0.1° and 0.5°/second. The delay in perception of velocity and acceleration change is greater for the vestibular sense than for the kinesthetic sense. For instance, with an angular acceleration of 10°/second^2, motion perception occurs in about 1 second; if the angular acceleration is only about 0.5°/second^2, it may take as long as 10 to 12 seconds to perceive the motion (see Figures 6-5 and 6-6).

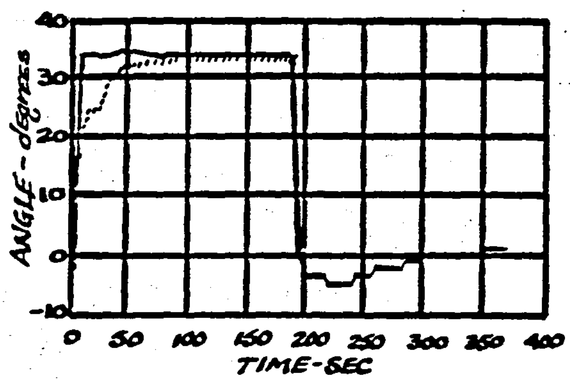


Figure 6-5: Perception of the Vertical by the Vestibular Sense (Graybiel, 1952)

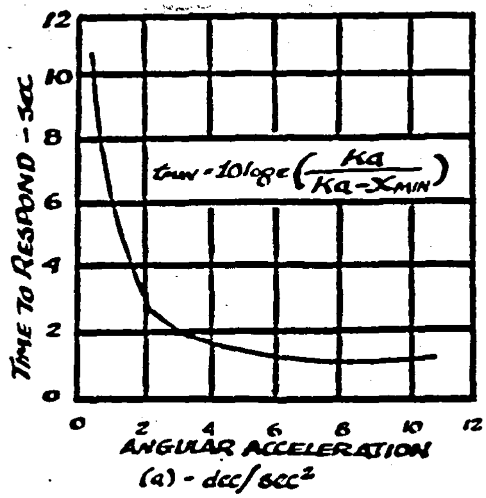


Figure 6-6: Thresholds for Sensing Rotation (Guedry and Richmond, 1957)

It is extremely important that the sensations provided by the vestibular senses not be in conflict with visual or kinesthetic sensations. Any conflicting sensations of this sort can lead to debilitating feelings of disorientation. Rotation of the body, tilting of the head when the body is rotating, rotation of the body opposite from that of a vehicle on which the person is riding, or vertical oscillation can result in profound disorientation and often motion sickness.

There are two main factors which can influence the kinesthetic and vestibular senses. While there are definite individual differences in sensitivity to kinesthetic stimuli, the most important source of variation is the result of the human's ability to learn to interpret these cues accurately. With enough practice a person can learn to position a control quite accurately without visual cues. Also, the absence or reduction of the earth's normal gravitational field results in the reduction or loss of many kinesthetic cues.

For design purposes, however, the capabilities of the kinesthetic and vestibular senses are most significant in the design of controls where they aid in the positioning of controls without visual cues. Both senses also provide some information for the attitude and change of motion of vehicles. When designing vehicles, the most important consideration is to avoid rotations or oscillations which are conflicting or disturbing or may cause motion sickness (Ref. 15).

6.1.2.2 Tactile Sense

Touch sensitivity is a function of deformation of the skin. The determination of touch thresholds is dependent on the rate at which the skin is deformed. That is, the absolute threshold is lower as a stimulator is pressed against the skin more rapidly than if pressure is applied slowly. As a result, if the stimulator is applied slowly enough, the individual will be unaware of the pressure. Once a constant pressure is reached, the sense will adapt and awareness of the contact will cease.

The absolute threshold of touch varies considerably with the part of the body being stimulated (see Table 6-3).

Table 6-3: Absolute Thresholds for Tactile Stimulation (Woodson, 1981)

Region	Pressure, 3/mm^2
Tip of Finger	3
Back of Finger	5
Front of Forearm	8
Back of Hand	12
Abdomen	26
Back of Forearm	33
Thick Part of Sole of Foot	250

The perception of two or more pressure points as separate (the difference threshold) for touch are difficult to establish. In general, the separation increment is smaller for that body surface which displays the higher absolute sensitivity (see Table 6-4).

Table 6-4: Amount of Pressure Relative to Accuracy of Judging Location (Woodson, 1981)

Region	Weight 12 g	27 g	40 g	57.5 g	67.5 g
Back of hand:					
Mean	7.21	6.93	6.86	6.69	6.76
Standard Deviation	4.7	4.6	4.4	4.3	4.4
Volar surface of forearm:					
Mean	7.19	7.13	6.14	6.75	6.59
Standard Deviation	4.5	4.5	3.7	4.1	3.8

6.1.2.3 Strength

The design of a system predetermines the nature of the physical activities that will be required to operate it. These activities include the energy costs, the range of motions and their strength, endurance, speed and accuracy requirements. Timely consideration given to these factors during the design process may result in dividends in later system performance.

Strength is the maximal force muscles can exert isometrically in a single voluntary effort, or the muscular capacity to exert force under static conditions (Ref. 12). Muscle force is a function of several variables, some of which are:

Muscle tension - is maximum when the length of the muscle is greatest and there is no change in the length for a period of time. Muscle force decreases as the rate of shortening increases.

Mechanical advantage - occurs at the midpoint of full elbow travel. This is because optimum mechanical advantage more than compensates for the shortened muscle.

Thermal environment - When humidity is high and temperatures exceed 85°F, strength is adversely affected. Low temperature, however, has little impact except in relation to body mobility and finger dexterity.

Acceleration - Accelerations up to 5 g's do not affect strength but do affect endurance. Arm movements are effective up to about 6 g's and wrist and finger movements are effective up to about 12 g's.

Emotional condition - Strength may increase under stresses such as fear, panic and rage; but skill and accuracy are degraded.

Body and limb position - Since there is usually a reciprocal response during force applications (e.g., lifting, pushing and pulling), it is important to provide adequate support and anchoring. Limb position and direction of force application are the most important variables in determining the amount of force an individual is capable of applying. They must be considered together for each specific operational requirements (Ref. 10).

The revelance of human strength to the design of teleoperator systems lies in the consideration of control operability. The maximum resistance of a control should be low enough to be overcome by the weakest operator. Under no condition should this value be exceeded. "Operational" or "optimal" resistance levels should not require the application of maximum power by the operator, however. Operational resistance levels significantly impact comfort and efficiency. Resistance should therefore be low enough to prevent fatigue or discomfort, but high enough to prevent inadvertent operation of the control and to provide sufficient kinesthetic cues to control movement (Ref. 6).

Table 6-5 presents guidelines for the most effective levels of resistance of controls likely to be used in the design of teleoperators (Ref. 13).

Table 6-5: Some Control Functions and Recommended Operating Resistance (MIL-STD-1472C, 1981)

CONTROL	RESISTANCE Minimum	Maximum
Rotary (discrete)	1.0 in-lb	6.0 in-lbs
Rotary (continuous)	4.5 in-oz	6.0 in-oz
Thumbwheel (discrete)	6.0 oz (.17 kg)	20.0 oz (.57 kg)
Thumbwheel (continuous)	-	12.0 oz (.34 kg)
Pushbutton (single finger)	10.0 oz (.28 kg)	40.0 oz (1.1 kg)
Pushbutton (different finger)	5.0 oz (.14 kg)	20.0 oz (.57 kg)
Pushbutton (thumb or palm)	10.0 oz (.28 kg)	80.0 oz (2.27 kg)
Keyboard (numeric)	3.5 oz (.1 kg)	14.0 oz (.4 kg)
Keyboard (alphanumeric)	0.9 oz (.026 kg)	5.3 oz (.15 kg)
Keyboard (dual function)	0.9 oz (.026 kg)	5.3 oz (.15 kg)
Toggle Switch (small)	10.0 oz (.28 kg)	16.0 oz (.45 kg)
Toggle Switch (large)	10.0 oz (.28 kg)	40.0 oz (1.1 kg)
Rocker Switch	10.0 oz	40.0 oz (1.1 kg)
Slide Switch (small)	10.0 oz	16.0 oz (.45 kg)
Slide Switch (large)	10.0 oz	40.0 oz (1.1 kg)
Joystick	12.0 oz	32.0 oz (.9 kg)
Lever (one hand/push-pull)	2.0 lbs	30.0 lbs (14 kg)
Lever (two hands/push-pull)	2.0 lbs	50.0 lbs (23 kg)
Lever (one hand/right-left)	2.0 lbs	20.0 lbs (9 kg)
Lever (two hands/right-left)	2.0 lbs	30.0 lbs (14 kg)
Trackball (precision required)	1.2 oz (preferred value)	3.5 oz (.1 kg)
Trackball (vibration or accel. condition)	-	6.0 oz (.17 kg)

6.1.2.4 Endurance

Endurance is the ability to continue work or exert force over time. There is a nonlinear, inverse relationship between the fraction of the strength which must be exerted and the time over which is can be exerted. One hundred percent of strength can be exerted for only a few seconds; only a fraction (15%-20%) of maximal strength can be maintained for several hours without fatigue.

6.1.2.5 Dexterity

Designers should be constantly mindful of the fact that where the operation of equipment is highly dependent on manual dexterity or skill and practice, there is considerable opportunity for error. The equipment should therefore be designed so as not to place unreasonable demands on dexterity, precision, speed, or highly sensitive responses to a wide range of cues. It is important to understand the characteristics of the human sensorimotor servosystem and design so that lags in the human system are taken into account.

Many manual skills are especially degraded when the specific human-product relationship is not optimum. This relationship refers to the position of the operator in relation to the task, the extent and direction of movement, the rate of movement, and the rate of change of movement. Manipulatory requirements beyond nominal capacities may cause increased physical and mental strain. This psycho-physical state will reduce the ability to coordinate body, limb, hand and finger movements, as well as the ability to make precise direction, rate and force inputs. It also reduces attention and perceptual awareness of errors. All human-machine design relationships should be "natural," convenient, and within the bounds of reasonable demands.

Although the average person may perform certain control manipulations more accurately than others, considerable dexterity may be developed with practice. In general, performance levels can be expected as follows:

1. Rotational manipulation is more accurate than either sliding manipulation or movement of thumb or finger wheels. Performance with thumb or finger wheels, in turn, is more accurate than with sliding manipulation.

2. Rotation in a horizontal plane is more accurate than rotation in the vertical plane. Horizontal accuracy depends on the ability of the operator to rest his or her hand on the adjacent surface.

3. A pushbutton is located and pressed more accurately when positioned in a horizontal plane.

4. A pencil-sized joystick is manipulated more precisely than one requiring a full fist grip. The accuracy is also increased significantly if the operator's arm can be rested on a nearby horizontal surface (Ref. 6).

6.2 PSYCHOMOTOR LEARNING AND FEEDBACK

Skills which involve motor activity are generally characterized by three features: the organization of sequences of motor movements and/or symbolic information; a purpose, goal or desired target state toward which the sequence is directed; and, corrective reactions based on feedback from the consequences of previous actions.

6.2.1 Hand Control

The operation of teleoperator systems may be considered to be a continuous adjustment control response. Control effectiveness in this case depends on several factors:

- The ability of the operator to anticipate and predict what is going to happen when input is provided to the system.
- Feedback on a timely basis about what is happening as control inputs are made.
- The amount of differentiation, integration and/or algebraic addition the control and display task requires of the operator. These should be minimized.
- How well the specific control and display devices provide compatible relationships between the operator's sensory, perceptual and motor and physical abilities and limitations.

It is important to be cognizant of the following factors which degrade control effectiveness:

- Long delays between inputs and feedback, e.g., perceived changes in incoming information, results of operator inputs on system, or direct feedback from controller manipulation.
- Too much noise in the system, e.g., extraneous signals, dynamic disturbances, or mechanical artifacts such as "dead space," "stiction," and force irregularities.
- Incompatibilities between control and display direction and rate of motion.
- Controller force requirements are too high or too low.
- Incompatibility of the position, direction, and range of movement of the controller with operator's position and physical capabilities.
- A requirement that an inappropriate body element be used, e.g., the hand versus the foot, the left hand versus the right hand, or the whole limb versus the hand and fingers.

There are some general statements about human interaction with continuous adjustment control activities which should also be considered. Humans seem to be more efficient when:

- o They can make large motions. This is because their own proprioceptive feedback mechanisms provide significant information about what they are doing.
- o The movements they make are in the same direction in which the object, system, or displayed element moves.
- o The rate of change of their control movement is similar to that of the controlled object or displayed element.
- o Sufficient information is supplied to allow them to predict what is going to happen if they maintain their present control input and/or modify it to some extent. In order to predict, the operator must also know the general limits of their control system's response range.
- o The control forces are not too high and are approximately equal throughout the controller movement range. For instance, high initiating forces (stiction) require the operator to suddenly compensate, once the controller is put into motion.
- o There is some friction in the control system to minimize the effect of external dynamic disturbances along with their own spurions autonomic responses caused by tumor, fatigue, etc. Variable forces within certain systems may be desirable, however, in order to provide the operator with cues relative to the position or condition of the system; for example, increasingly higher forces as controls approach their limits.
- o They are properly positioned and secured in relation to the apparatus. That is, a seated operator with appropriate hand-rests or armrests is less influenced by dynamic disturbance and by problems of maintaining body equilibrium.
- o They primarily rely on hand and finger movement to manipulate a controller when small, accurate actions are required.
- o They are not required to manipulate too many separate controls in an integrated manner. Operators should not be required to perform sequential operations of several hand and/or foot controls while at the same time carrying out a primary task.
- o They do not have to hold a control device with their arms or legs suspended for long periods of time; or hold the control in a fixed position for extended periods.

- They are provided appropriate system aids (e.g., predictive displays) which relieve them of complex mental information processing such as differentiating, integrating, extrapolating or performing algebraic additions during the control tasks (Ref. 10).

6.3 AUDITION

The nature of the auditory sensory system offers unique advantages for the presentation of information as contrasted with the visual system. This section will discuss the physiology of hearing, the parameters of audition, and recommendations for the use of auditory displays.

6.3.1 Physiology of Audition

Sound waves first travel through the outer ear and auditory canal to a thin membrane (the eardrum) which starts to vibrate. The vibrations of the eardrum are picked up by three small bones (the ossicles) in the middle ear and are transmitted through another membrane (the oval window) to fluid in the auditory part of the inner ear (the cochlea). One of the ossicles (the stirrup) acts like a piston, moving the fluid back and forth with the rhythm of the sound waves. The movement of the fluid makes a thin membrane within the cochlea (the basilar membrane) vibrate. This, in turn, bends a type of hair cell which rests on the basilar membrane. These hair cells are the actual auditory receptors. Their movement "excites" them and produces a generator potential which initiates nerve impulses in the fibers of the auditory nerve. It is the auditory nerve that carries the impulses to the brain (Ref. 14).

6.3.2 Parameters of Audition

The absolute threshold of hearing is a value which represents for audition the same concept as for other sensory modalities. It is the minimum sound- pressure level of a specified sound that is required to elicit the sensation of hearing in a specified fraction of trials (about 50%). The value of the absolute threshold depends on the type of sound (its frequency, duration, repetition rate, method of presentation) as well as characteristics of the listener.

There are, however, three generally accepted thresholds for pure tones. The Minimum Audible Pressure is the sound-pressure level measured at the eardrum of a trained listener when the stimulus is presented through earphones. Some argue that this is an artificial situation since the sound wave at the eardrum has already been amplified and distorted. The Minimum Audible Field is the level of the absolute threshold of a trained listener as measured where the center of the head would be when the source is a speaker placed in the room. The Normal Threshold of Audibility is the modal value of the minimum sound level at the entrance to the ear that can be heard by a large sample of untrained listeners wearing earphones. Figure 6-7 illustrates the relative values of Minimum Audible Field and Minimum Audible Pressure (Ref. 1).

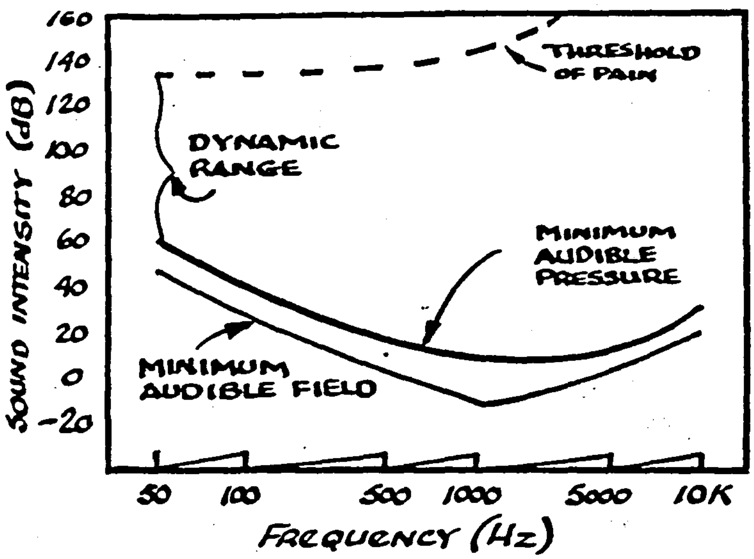


Figure 6-7: The Dynamic Range of Hearing from Minimum Audible Intensities to the Threshold of Pain (Based upon Sivian & White, 1933; Coren, Porac and Ward, 1978)

It is important to note in Figure 6-7 that the threshold varies as the stimulus frequency varies. The ear is most sensitive to sounds with frequencies between 2000 Hz and 5000 Hz and about 100 times less sensitive to sound at 100 Hz than to sound at 3000 Hz.

Hearing is generally considered a subjective phenomenon. The ear responds in a somewhat predictable fashion to physical sounds. That is, the objective measures of sound such as amplitude, pressure and intensity are subjectively perceived as loudness; sound frequencies are perceived as pitch; and, energy distribution is perceived as quality.

In order to determine the discriminability between two sounds, the two physical dimensions, intensity and frequency, must be separated. Studies of the difference threshold for intensity have shown that a discrimination ratio ($\Delta I/I$, or Weber fraction) of 0.33 best describes auditory performance. Figure 6-8 shows the variance in the Weber fraction over a range of intensities. The size of the fraction is smallest (or, discrimination is best) for stimuli in the middle range of frequencies. The auditory system is sensitive enough to detect a 20% change in stimulus intensity across a rather broad range of frequencies and intensities (Ref. 11).

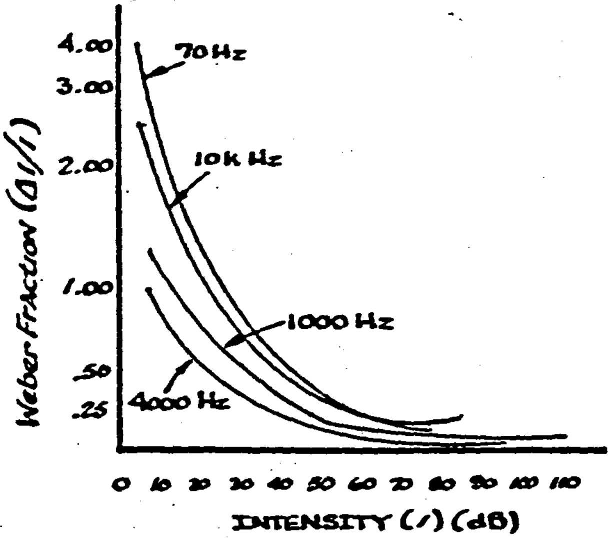


Figure 6-8: Intensity Discrimination Measured in Terms of the Weber Fraction for Various Intensities and Frequencies of Standard Stimuli (Based upon Riesz, 1928; Coren, Porac and Ward, 1978)

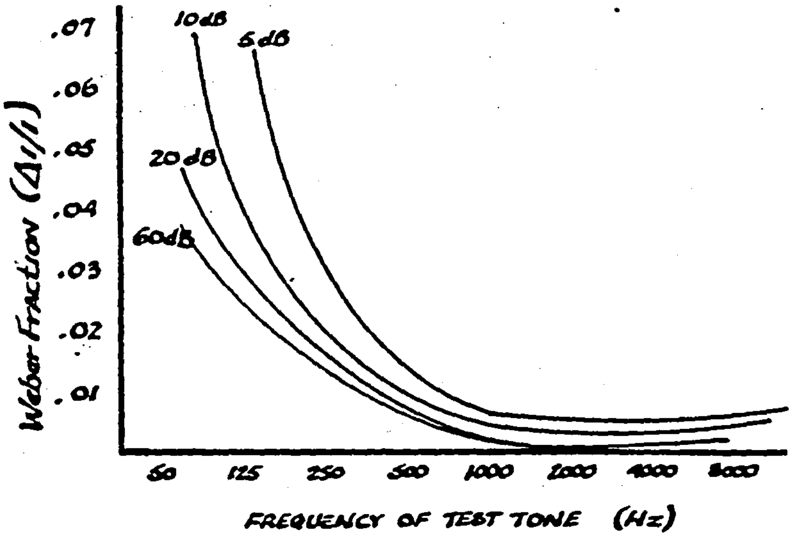


Figure 6-9: Frequency Discrimination Measured in Terms of the Weber Fraction for Various Intensities and Frequencies of Standard Stimuli (Based upon Riesz, 1928; Coren, Porac and Ward, 1978)

The ability to discriminate two tones of different frequency, as measured by f/f, is shown in Figure 6-9(above). It should be noted that at frequencies greater than 1000 Hz the Weber fraction is constant and very small (about 0.005). In other words, if a listener were presented with a tone with a frequency of 1000 Hz and another tone of 1005 Hz, this difference of half of one percent would be detectable. However, at lower intensity levels, the ability to discriminate frequency differences is not as accurate.

6.3.3 Recommendations for Use and Design of Auditory Displays

There are several conditions under which an auditory signal may be preferred to other types of visual signals:

- <u>As a warning signal</u>. A visual warning must be seen in order to be effective. Alternately, hearing is omnidirectional and cannot be involuntarily turned off. It is, therefore, the best modality to which attention to imminent or potential danger should be called.

- In situations where one visual display has nearly complete attention of the operator or when too many visual displays are already presented.

- Where information must be presented independently of head orientation, as in cases where duties require body movement or head training.

- Under conditions of anoxia or high positive g forces. Audition is more resistant to anoxia than vision.

- When signals must be distinguished from noise.

- When the information provided is short, simple and transitory and requires immediate or time-based responses.

- As a redundant or supplementary transmission of critical information.

- Where custom or usage has created an anticipation of an audio display (Refs. 6 & 13).

The effective design of an auditory display must give proper consideration to the sound environment within which it will operate. An auditory signal can otherwise be easily obscured by extraneous noise or sounds in the environment. The frequency range should be between 500 Hz and 3000 Hz. Whatever frequency band is selected should differ from the most intense background frequencies.

If the auditory signal is to be used as an auditory code, certain signal conventions should be followed. For example, high frequencies should be associated with "up" and low frequencies should be associated with "down." If the auditory codes have a more arbitrary assignment to a condition, then it is preferable that the signals be discriminable in intensity, pitch, beats and harmonies. Also, the number of signals to be discriminated should not exceed four. Once a particular auditory code has been established for a given operating situation, the same signal should not be designated for some other display.

6.4 THE SENSES OF TASTE AND SMELL

The use of olfactory (smell) sensitivity has had some application in the detection of hazardous conditions, e.g., fumes of toxic gases. However, both taste and smell show nearly complete adaptation with continued exposure to the same substance. Therefore, they should not be relied upon as sources of information. In some situations the first indication of an equipment malfunction may be through the olfactory sense, e.g., the smell of burning insulation. However, this capability of the human sensory system is hardly reliable enough to use as a basis for design, and no use for the senses of taste or smell is recommended in the design and operation of teleoperator systems (Ref. 6).

6.5 TRANSFORMATION OF INFORMATION TO PERCEPTIBLE FORMATS

The way in which any sort of equipment is designed to present information to the human component of a system must be related to the parameters of the human sensing system. These parameters not only vary among sense organs, but also among individuals. Therefore, special consideration must be given to these factors in order to determine functional engineering specifications.

The human sensing system is in many ways extremely accurate, versatile and sensitive. There are, however, many circumstances in which information critical to the performance of some activity must be presented indirectly by the use of some type of display.

1. When stimuli from the environment are such that they are beyond human sensory capabilities entirely. These stimuli (e.g., electromagnetic radiation beyond the spectrum to which humans are sensitive and ultrasonic vibrations) must then be sensed by specialized sensing devices and converted to an appropriately coded form for human perception.

2. When stimuli are of the type that humans can generally sense, but are not able to sense adequately. The following factors would cause such a condition:

   a. Stimuli at or below threshold values that need to be amplified by electronic, optical or other means (e.g., stimuli are too far, too small or insufficiently intense).

   b. Stimuli that require reduction for adequate sensing (e.g., very large operational areas).

   c. Stimuli embedded in excessive noise need to be filtered or amplified.

   d. Stimuli may need to be sensed with greater precision than the human senses are capable of discriminating (e.g., temperatures, weights and measures, sound, etc.).

   e. Stimuli need to be precisely stored for future reference (e.g., photograph, recording).

   f. A certain stimulus may be more easily or more conveniently sensed if converted to another type of stimulus which is either in the same sensory modality (e.g., a graph to represent quantitative data) or in a different modality (e.g., an auditory warning signal).

   g. Information about events or circumstances may require a display presentation by their very nature (e.g., emergencies or hazardous conditions) (Ref. 12).

Although a design meets or exceeds a sensory threshold for detection or differential sensitivity, it still may not be adequate for sensing under adverse operating conditions. A designer may assume that, having attained threshold levels, any further increase may be a luxury. While this assumption may be valid under ideal conditions, it is not likely to be the case in an operational environment where stress or boredom are added. For this reason, human factors specialists test designs under conditions as nearly like the operational environment and workload as possible prior to acceptance of the final design (Ref. 6).

Table 6-6 lists eight key sensing parameters, their more important implications for engineering design, and the classes of equipment that would be affected.

Table 6-6: Implications of Sensing Subsystems Parameters of Equipment Design (VanCott & Kinkade, 1972)

Parameter	Implications of parameter for equipment design	Equipment affected
Detection sensitivity (lower threshold).	Defines minimal intensity and frequency of signals that can be detected by a sense organ.	Alarms, voice, and visual displays.
Detection sensitivity (upper limit).	Defines limit on intensity and frequency beyond which sensitivity is lost and/or damage may occur to sense organ	Alarms, ambient illumination, protective equipment (e.g., goggles, ear protectors), noise suppression.
Differential sensitivity (difference threshold).	Defines intensity or frequency by which: (a) signal A must be increased or decreased for the change to be detected, (b) signals A and B must differ to be detected.	Scope resolution, scale, and pointer design.
Sensitivity range (upper limit minus lower threshold).	Defines maximum "bandwidth" of a physical energy that can be used for signal presentation & display purposes.	Voice communications equipment (headsets, speakers); visual displays (e.g., sonar, radar, photogrammetry, etc.).
Information transmission capacity.	Determines maximum number and type of codes possible within a stimulus dimension. Determines maximum rate of information presentation. Determines maximum rate of operator decision-making.	Map, display board, and scope symbology; coded warning signals; information update rates; desirability of control dynamics to aid operator response; amount of information presented.
Speed	Determines maximum rate of information presentation, operator response speed, and system response.	Determines information presentation & update rate.
Reliability	Affects overall design, utility, and cost of system.	All man-machine interfaces.
Variability	Information presentation parameter values must be selected on basis of performance of "typical" operators.	All man-machine interfaces.

6.6 INFORMATION PROCESSING

A human being can be thought of in one sense to be an information processing system. Within the context of man/machine systems, two parameters of information processing are of interest: the amount of information that man can transmit/receive and the rate at which it can be transmitted/received.

The amount of information is often expressed in "bits." A bit is the logarithm to the base two of the number of equally likely alternatives. The number of bits is equal to the number of two-choice discriminations required to specify a particular event from alternative ones. Unless there is a proper distribution of information between the human component and the other parts of the system, the operator may either be overloaded with information he is incapable of processing at all, or be unable to process the information rapidly enough.

The amount of information transmitted through a "human channel" can be calculated in much the same way as it would be for electromechanical systems. Humans can transmit about 5 to 10 bits of information per second. They transmit two bits per second (b/s) when the stimuli they receive are fairly well structured. Four bits per second can be obtained by adding appropriate coding to the input. An operator can accept no more than two or three items of data per second (Ref. 10).

Many investigations have been conducted in order to determine the transmission limits of various stimuli. Several conclusions may be derived from the results of these studies. For instance, the channel capacity of vision is higher than for any other sense. Also, within a given sense, different stimulus dimensions are associated with different capacities for transmission. This is because a sense organ has a greater capacity to transmit information when there is a wide range between the upper and lower detection thresholds. Third, the number of absolute judgments that can be made along any one dimension varies widely among senses as well as among stimulus dimensions. That is, the human eye can reliably identify at least 13 different colors; it can only identify five different brightnesses. The application of this knowledge means that color codes can convey more information than brightness codes (Ref. 6).

There are many circumstances or types of systems for which the rate of information transmission or response time is critical to system performance. As the speed of information processing demand increases, the number of errors committed by the operator also increases.

Some of the factors which affect human reaction time include:

- The sense used
- The characteristics of the input signal
- The signal rate
- Whether or not anticipatory information is provided
- The response requirements of the task
- Individual differences in age, sex, training, and experience.

Generally, reaction time is shortest when simple, conspicuous signals are used. Reaction time increases as the number of signals to be attended to increase or as signal intensity decreases (Ref. 6).

The types of errors related to information processing which may occur may be classified as follows:

- o Failure to detect a signal. This may be caused by an input overload or underload and/or actual interference.
- o Misidentification - caused by insufficient cues, identifying a non signal as a signal.
- o Improper weighting of informational factors and/or selection of input factors - caused by poor or inadequate conceptualizations or evaluation of action choices.
- o Action failure - Caused by a wrong action at the right time or a right action at the wrong time (Ref. 10).

6.7 EFFECTS OF PSYCHOLOGICAL AND ENVIRONMENTAL FACTORS ON PERCEPTION AND PERFORMANCE

A given display or control does not directly transmit information to the operator; they present stimuli which are received and then interpreted as meaningful or not. Human abilities to deal with the onslaught of stimuli from the environment depend to a large extent on perceptual and mediational processes as well as on sensory processes.

6.7.1 Workload

Workload is a function of speed and loading of tasks or stimuli to which the operator must attend. Load refers to the type and number of tasks. Speed relates to the time available per task.

It has been shown that both speed and load are directly related to errors. To explain these rather consistent results, the concepts of speed stress and load stress have been posited. Speed stress is the behavioral reaction which has the effect of worsening performance on a task beyond that which might be expected given the physical parameters of the task. Alternatively, load stress actually changes the character of the task. As stress due to increased workload increases, performance declines markedly in terms of errors and response time (Ref. 12).

6.7.2 Stress

Stress refers to any aspect of human activity or the environment which may act on an individual and which results in some undesirable cost or reaction. Possible sources of stress can be either physiological or psychological in nature. Physiological causes of stress inherent in a task may include heavy, strenuous physical labor or complete immobilization in the extremes. Environmental sources of stress may be the atmospheric conditions, noise and/or vibration levels, and heat and cold. Sleep loss is another stress factor when circadian rhythms are seriously disrupted for extended periods (Ref. 6).

6.7.3 Motivation

Generally, research and discussions of the laws of perception have strictly dealt with the determinants of perception such as the stimulus, stimulation at the retina or other receptor points, or other aspects of the innate endowment of the human and characteristics of the physical stimulus energy. However, between the sensory receptors and motor effectors there is a human being with motives, needs, values, attitudes and expectations which can influence perception in important ways. As discussed in Section 6.1.1, expectancies, intrinsic reinforcement contingencies, and stimulus conditions can influence performance. Controlled studies have consistently shown a tendency toward perceptual accentuation of a valued characteristics. The active role of emotional and motivational factors in perception can dramatically effect perception and performance (Ref. 14).

6.7.4 Environment

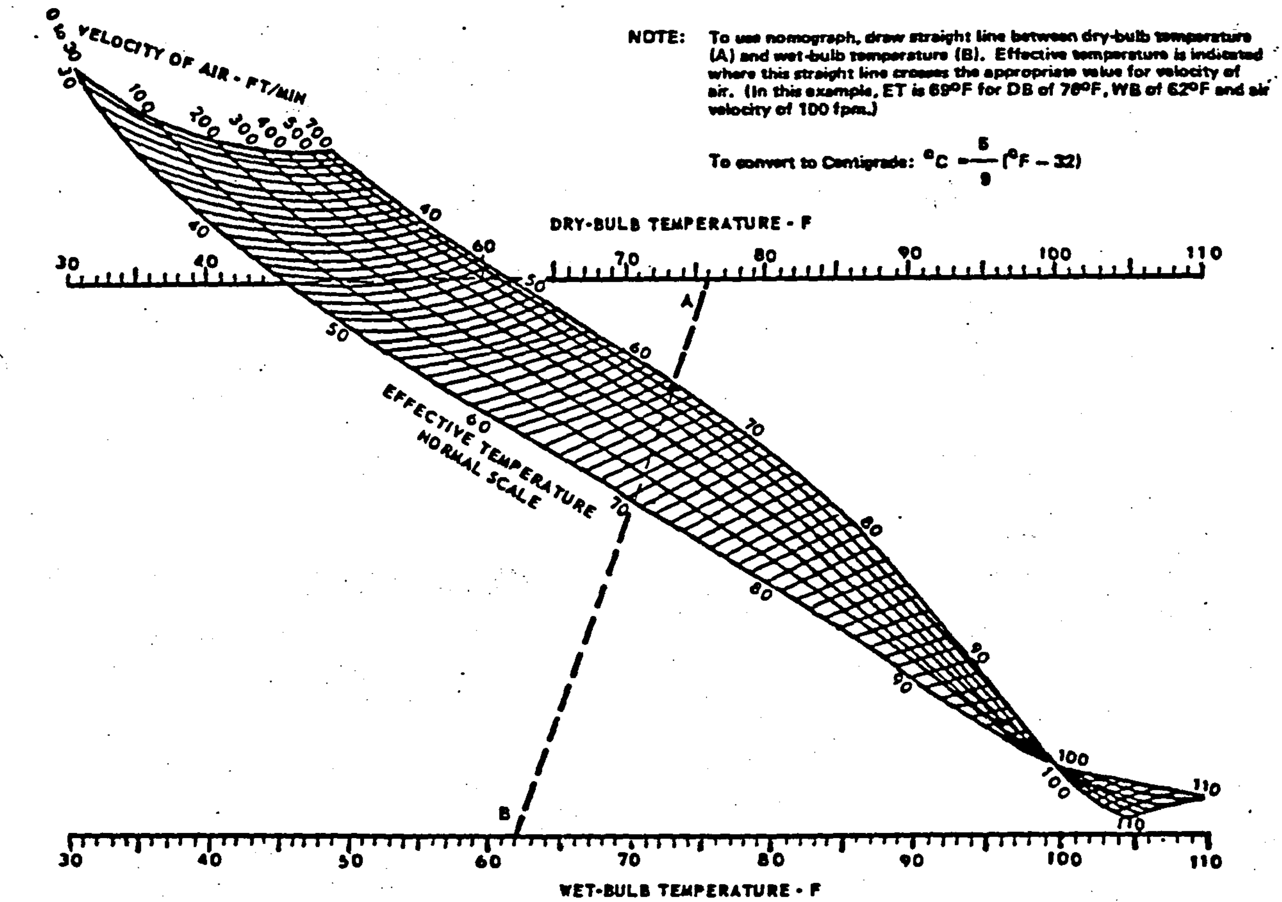
Humans have a range of adaptability and tolerance of environmental stresses within which they can operate without depending on the emergency maintenance systems of the body and with no appreciable effect on performance. The problem is not one of adaptation, but rather the limits and costs one pays for adaptation to conditions which represent stresses on adaptive mechanisms.

Various environmental stressors affect psychological and behavioral mechanisms such as sensing, classifying, storing, and retrieving information, and selecting and executing responses in different and contrasting ways. While one stressor may reduce performance rate but not affect error rate, another may increase errors without affecting the rate of performance.

The effects of noise on human performance have been found to depend to a large extent on the type of noise involved. For instance, research has shown that noise may interfere with, improve or have no effect on low-input tasks, such as vigilance tasks, depending on its intensity, continuity and the length of time continuously on the job. Noise has been shown to interfere with performance on high-input tasks in that the number of errors may increase but the rate of response will be unaffected. Typically, only loud noises have been found to interfere with performance by increasing the amount of errors made. It is assumed that errors occur during momentary shifts of attention to noise source. When the sound is irrelevant to the task, high frequency noises tend to be associated with more errors than lower frequency noises. However, when the sound is relevant, i.e., a tone signaling a response, high frequency tones produce faster reactions than lower frequency tones. People experience the greatest annoyance from high frequency, intermittent noise (Ref. 15).

Air temperature is another environmental factor with a potential impact on human performance. Subjective impressions of heat and cold are actually determined by a combination of temperature, humidity, and air movement values.

The heating/air conditioning systems should maintain a temperature value between 18°C and 29°C. Humidity values should approximate 45% at 21°C. Air flow systems should introduce at least 0.85m^3 per minute per person at a velocity not more than 30 m per minute. The following graph can be used to determine the most appropriate effective temperature given the interaction effects of all of the variables (Ref. 13).



Clothing: Customary indoor clothing. **Activity:** *Sedentary or light muscular work.* **Heating Methods:** *Convection type, i.e., warm air, direct steam or hot water radiators, plenum systems.*

Figure 6-10: Effective Temperature
(MIL-STD-1472C, 1981)

6.7.5 Control/Display Design and Format

Effective and efficient man-machine systems depend upon equipment design features which make full use of human performance capabilities and also recognize human limitations. From a system's point of view, human capabilities and limitations are seen in terms of receiving, coding and transmitting information which interface with machine components of the system. Although both the human and machine components are subject to factors in the physical environment, humans are particularly affected by conditions which may overstress or understimulate them. Environmental factors, physiological factors and task demands interact to determine the total load on the operator.

An information overload for the operator can result from too many signals carrying too much information from too many sources. It may be due to inadequate or inept coding of displays, controls, or the display-control arrangement. Thus, appropriate design of controls and displays and compatible control-display arrangements are fundamental to the optimal design of a human-machine system.

The criteria for design are dependent to a large extent on mission requirements and other factors external to the system. However, a body of knowledge has been developed which addresses specific design in the determination and application of human factors engineering guidelines to a teleoperator system:

- MIL-STD-1472C, Human engineering design criteria for military systems, equipment and facilities. 1981.
- Woodson, W.E. Human factors design handbook. McGraw-Hill, Inc., New York, 1981.
- VanCott, H.P. and Kinkade, R.G. (Eds.). Human engineering guide to equipment design (Rev. ed.). American Institutes for Research, Washington, D.C., 1972.
- McCormick, E.J. Human factors engineering. McGraw-Hill Book Company, New York, 1970.
- Chapanis, A. Man-machine engineering. Wadsworth Publishing Co., Inc., California, 1965.
- Woodson, W.E. and Conover, D.W. Human engineering guide for equipment designers. University of California Press, Berkeley, California

7.0 ADDITIONAL SIMULATION FACILITIES

7.1 INTRODUCTION

Through simulation, the duplication of known or expected mission variables into a training or research program has provided a low cost, low risk means of investigating overall system performance. Simulation is widely used in aerospace programs to train pilots and astronauts in flight procedures and to verify the interaction of the human operator with the hardware components in the accomplishment of the proposed mission objectives.

In support of the design, development, integration, and validation of space teleoperator systems, simulation capabilities can be classified in terms of their basic purpose, such as:

- o Research on human capabilities, requirements and roles
- o Teleoperator technology development
- o Teleoperator system integration
- o Teleoperator system validation.

Through the MSFC Teleoperator Technology Development Program, simulations of teleoperator missions have included satellite capture, retrieval and servicing, Shuttle mission support and servicing, structures assembly and structures payload servicing, and support of space station operations. The majority of the simulation data has been collected in the visual, manipulator and mobility laboratories which were described in earlier sections of this document. There are four additional test and simulation facilities which warrant note for teleoperator system investigations: the Neutral Buoyancy Simulator (NBS)facility, the Six Degrees-of-Freedom (DOF) Motion Base Simulator, the Target Motion Simulator (TMS), and the proposed Teleoperation and Robotics Evaluation Facility. These facilities are described below.

7.2 NEUTRAL BUOYANCY SIMULATOR FACILITY

MSFC'S Neutral Buoyancy Simulator facility is a 1.4 million gallon water tank in which system mockups can be made neutrally buoyant, simulating low gravity conditions. The simulator provides an environment where six degrees-of-freedom motion can be achieved for free flying mockups, EVA operations by suited test subjects, remote manipulator system operations, and similar large scale simulations. The 75-ft diameter and 40-ft. depth of the tank provides ample room for simulations of Shuttle payload bay operations, including the remote control of payloads. In the past, free flying vehicles have "flown" in the NBS powered by underwater motors representing thruster modules.

Given appropriate calculations to overcome or describe the water drag characteristics and careful selection and buoyancy of the test article or mockup, the NBS is an especially good facility for extended simulations and multiple replications of teleoperated tasks. It provides a low cost, relatively uncomplicated environment for verifying teleoperator system concepts and for examining the human operator's capabilities in conducting 6 DOF remote tasks.

While teleoperator system testing in the NBS has been limited to some free flying concept examinations, the characteristics of the NBS lend itself to teleoperated assembly of Large Space Systems (LSS), teleoperated capture and retrieval of large mass satellites, and teleoperator/RMS cooperative tasks.

When simulations of remotely controller tasks require a high degree of motion control or require very fine adjustments in movement, the problems inherent in working in the NBS can be overcome by performing part task simulations on a 6 DOF motion base simulator.

7.3 MOTION BASE SIMULATOR

The 6 DOF motion base simulator is a hydraulically actuated motion table located at the MSFC Computation Laboratory. Originally designed as a flight simulator to provide acceleration cues to flight crew members who occupied the attached flight deck, the motion table has undergone modifications to accommodate control of teleoperated activities. During the Skylab reboost effort, the Teleoperator Retrieval System (TRS) capture device was mounted on the motion table and the Multiple Docking Adapter (MDA) was attached to a ceiling frame over the motion table. A remotely located operator controlled final approach and docking via television displays and two hand controllers. The performance characteristics of the motion system are shown in Table 7-1 for each of the degrees of freedom.

Table 7-1: Motion Table Performance Characteristics

	POSITION	RATE
Pitch	+30°, -20°	±15°/sec.
Roll	+22°, -22°	±15°/sec.
Yaw	+32°, -32°	±15°/sec
Vertical	39 in. up, 30 in. down	±24 in./sec.
Lateral	±48 in.	±24 in./sec.
Longitudinal	±48 in.	±24 in./sec.

The range of motion is not as large as that available in the NBS but the control and accuracy of motion are much greater; consequently, for terminal tasks such as final docking, remote structure mating or grappling, it is preferable in terms of data reliability to use the motion base simulator.

With appropriate modifications to the simulator table, a very wide range of remote tasks can be simulated and the controlling hardware and software can accommodate proximate remote tasks such as final docking or capture. With appropriate software, however, the simulator can accommodate evaluations over two or three times the physically constrained distance of the available movement of the motion base table. For approach distances greater than these, there is yet another general purpose simulator available at MSFC for teleoperator system evaluation, the Target Motion Simulator.

7.4 TARGET MOTION SIMULATOR

The Target Motion Simulator (TMS) located in the Computational Laboratory provides the capability to simulate distant approaches with considerable rate and position accuracy. It is most simply described as a target gimbal (roll, yaw, pitch) and a camera gimbal (roll, yaw, pitch) that travel along two translation rails. The simulator generally operates at 48:1 scale and the operating characteristics for this are shown in Table 7-2, while a general sketch of the TMS is shown in Figure 7-1.

Table 7-2: Target Motion Simulator (Gimbal/Track) Performance Characteristics

MOTION SERVO	POSITION TRAVEL	POSITION ACCURACY	MAXIMUM VELOCITY
Target Roll	± 180°	± ½°	± 50°/sec.
Target Yaw	± 90°	± ½°	± 10°/sec.
Target Pitch	± 90°	± ½°	± 10°/sec.
Camera Roll	± 180°	± 1°	± 75°/sec.
Camera Yaw	± 90°	± ¼°	± 5°/sec.
Camera Pitch	± 90°	± ½°	± 5°/sec.
Linear Motion (48:1 scale)	500 ft.	± 8 in.	±100 ft./sec.

The operator "flies" the camera toward the target and the computer resolves the command inputs into target and camera translation and attitude changes. The singular disadvantage with this simulator is that actual docking cannot be accomplished at the conclusion of a long approach task. For this, the simulation control must be switched to the motion base simulator for the final closure and docking. The controlling software can accomplish this scene transition without total disruption of the simulation, but there is a noticeable shift in the scene and the definition of the viewed target as the scene shifts from a 48:1 scale model to a 1:1 mockup.

Careful test setup, software programming and mockup and model work is required for an appropriate teleoperated simulation. Some margin of error must be attributed to changing simulators when performing approach and docking tasks, but with forethought and planning. Very successful simulation data can be derived from these facilities.

With the completion of planned simulation facilities at MSFC, even higher fidelity simulations will be practicable. A short description of these proposed facilities and the expected capabilities is given in the following section.

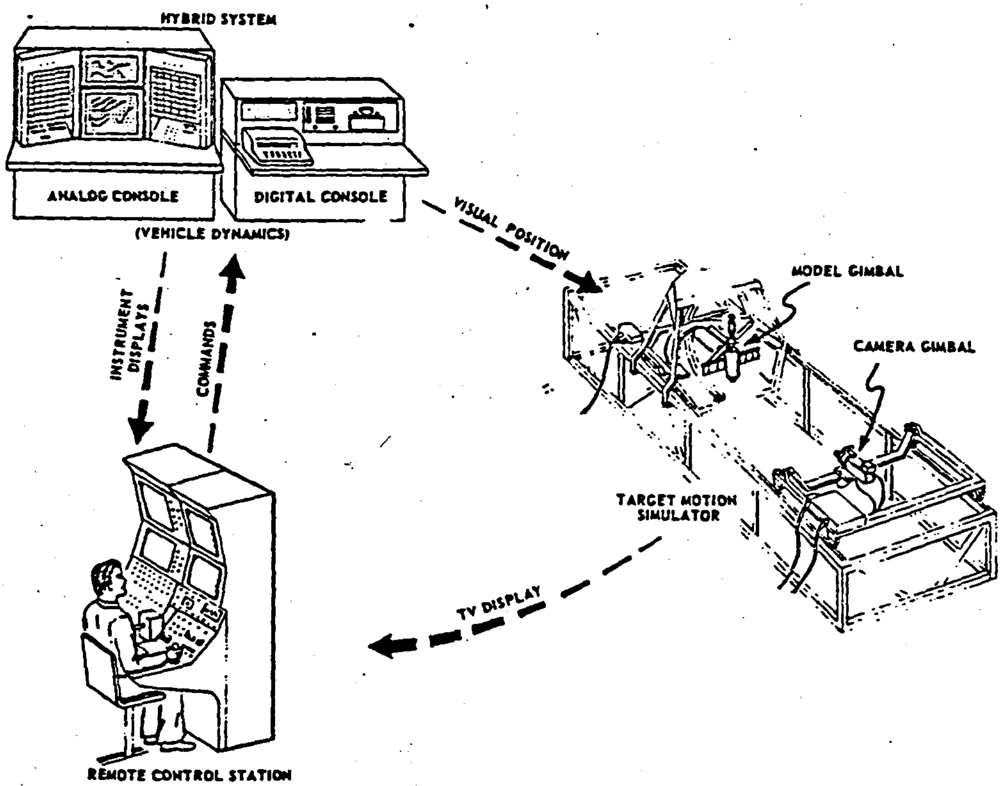


Figure 7-1: Target Motion Simulator

7.5 PROPOSED TELEOPERATION AND ROBOTICS EVALUATION FACILITY

During 1980-1981, architectural and engineering drawings were developed for an extensive simulation facility in MSFC's Building 4619. The facility will build on developed technologies from the several separate simulation facilities such as air bearing floors, variable drive simulators, precision targets, gimbals, 6 DOF mobility units, manipulator and visual system evaluation facilities, and computational facilities. The advantages of the proposed integrated facility will be to perform large scale simulations without having to move from one simulator system to another nor contend with water drag on the test mockups as occurs in the NBS.

As currently envisioned, the Teleoperation and Robotics Evaluation Facility will have a 4000 sq. ft. air bearing epoxy floor capable of supporting the operations of several air borne mobility units. Additionally, a standoff area at the end of the epoxy floor will support large stationary systems such as the Automated Orbital Servicer or the Protoflight Manipulator Assembly System which can be used in concert with mobility units. A visual system evaluation area and visual system shop are planned for the facility as is a manipulator and hand controller evaluation area. Computational support will be available from the facility's analog and digital computers as well as microprocessors which can be integrated into the mobility and target units.

The facility will offer a wide variety of general purpose mockups such as the Multimission Modular Spacecraft and the Teleoperator Maneuvering System, with the capability to quickly change out mockups for special evaluations. The mobility units will permit active manipulation or grappling while still main- taining the commanded vehicle attitude, and this will also permit the operation of remote camera booms.

Advanced planning calls for the installation of a 6 DOF overhead target motion system which will permit simulations of flyarounds and other independent 6 DOF tasks. This will provide enormous simulation capability with a high degree of data reliability and validity.

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8.0 LIST OF REFERENCES AND BIBLIOGRAPHY

8.1 REFERENCES

1. "Equipment Specifications for Manipulator Assembly of Remotely-Operated Systems." MSFC Specification 50M23186, December 1974.

2. Dual TV Display Unit for the NASA Marshall Space Flight Center. General Electric Technical Report. G.E. Aircraft Equipment Division, Binghamton, New York, October 1975.

3. Charged Induction Device Television Camera 27892. General Electric Optoelectronic Systems, Syracuse, New York, July 1975.

4. Tewell, J.R. "Conceptual Design Study for a Teleoperator Visual System." Martin Marietta Corporation, Denver, Colorado, under Contract NAS8-29024, 1973.

5. Roese, J.A. and Khalafalla, A.S. Sterescopic Viewing with PLZT Ceramics, Ferroelectrics, Vol. 10, pp. 47-51, 1976.

6. VanCott, H.P. and Kinkade, R.G. (Eds.). Human Engineering Guide to Equipment Design (Rev. ed.). Washington, D.C.: American Institutes for Research, 1972.

7. Shields, N.L., Jr., Malone, T.B. and Kirkpatrick, M., III. Manipulator System Performance Evaluations. NBS Special Publication No. 459. Government Printing Office, Washington, D.C., 1976.

8. Free-Flying Teleoperator Breadboard Vehicle. S&E-ASTR-6-WP-7-73, July 1973.

9. Gibson, James J. The Senses Considered As Perceptual Systems. Houghton Mifflin Company, Boston, Massachusetts, 1966.

10. Woodson, W.E. Human Factors Design Handbook. New York: McGraw-Hill, Inc., 1981.

11. Coran, S., Porac, C. and Ward, L.M. Sensation and Perception. New York: Academic Press, 1978.

12. McCormick, Ernest J. Human Factors Engineering (4th Ed.). New York: McGraw-Hill, Inc., 1976.

13. U.S. Army Missile Command, for the Department of Defense. MIL-STD-1472C, Human Engineering Design Criteria for Military Systems, Equipment and Facilities. May 1981.

14. Ruch, F.L. and Zimbardo, P.G. Psychology and Life (8th Ed.). Glenview, Illinois: Scott, Foresman and Company, 1971.

15. Landy, F.J. and Trumbo, D.A. Psychology of Work Behavior. Homewood, Illinois, 1976.

8.2 TELEOPERATION AND ROBOTICS BIBLIOGRAPHY

1. Teleoperator Maneuvering System, Mark II Propulsion Module Study. 1982, NAS8-34581, Martin Marietta

2. Video Based Autonomous Rendezvous and Docking System. 1982, NAS8-34679, Martin Marietta

3. Pneumatic Inflatible End Effector. 1981, Patent #4,273,505, MSFC - Clark

4. Space Platform Berthing Mechanism Test Report. 1981, NAS8-33759, TRW - SP1165

5. Earth Orbital Teleoperator Systems Evaluation. 1981, NAS8-31848, Essex Corporation

6. Large Space Systems Man/Machine Assembly Analysis. 1981, NAS8-32989, Essex Corporation

7. Preliminary Engineering Report for Teleoperator/Robotics Systems Laboratory. 1980, MSFC Facilities Office

8. Teleoperator Maneuvering System Simulation Facilities. 1980, MSFC Electronics and Control Laboratory

9. Electrical Self-Aligning Connector. 1980, Pat. App. MFS-25211, MSFC - Clark

10. Teleoperator Maneuvering System Program Definition Activities. 1979, NASA/MSFC Teleoperator Task Team

11. Design Study of Teleoperator Space Spider. 1979, NAS8-32620, Martin Marietta

12. Development of Concepts for Satellite Retrieval Devices. 1979, NAS8-33073, Essex Corporation

13. Earth Orbital Teleoperator Systems Evaluation. 1979, NAS8-31848, Essex Corporation

14. Low Energy Deployment and Retrieval Study. 1979, Battelle

15. Teleoperator Maneuvering System Program Definition Activities. TMS Fact Book. 1979, MSFC

16. Standard Mission Destination for Sun Synchronous Satellites Study. 1979, Aerospace Corporation

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17. Space Shuttle Program Teleoperator Retrieval System Simulation Plan. 1978, NAS8-32821, Martin Marietta

18. TRS Systems Description Handbook for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

19. Realtime Simulation Report for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

20. Docking System Analysis for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

21. Teleoperator Retrieval System Verification Report. 1978, NAS8-32821, Martin Marietta

22. Simulation Requirements Document for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

23. Space Shuttle Program Teleoperator Retrieval System Mass Properties Status Report. 1978, NAS8-32821, Martin Marietta

24. Simulation Software Design Document VCMU Support Software Volume II for Space Shuttle Program Teleoperator Retrieval. 1978, NAS8-32821, Martin Marietta

25. Simulation Software Design Document Hybrid Computer Lab Software Volume I. 1978, NAS8-32821, Martin Marietta

26. Integrated Proceedings and RID Packages from Teleoperator Retrieval System. 1978, MSFC

27. Flight Program Design Document for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

28. TRS Mission Operations Requirements for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

29. Critical Items Document for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

30. Approved EEE Parts List Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

31. Failure Mode and Effect Analysis (FMEA) for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

32. Space Shuttle Program Teleoperator Retrieval System Nonstandard Parts Approval Request. 1978, NAS8-32821, Martin Marietta

33. Systems Hazard Analysis for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

34. Design Reference Mission Analysis for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

35. Detailed Mission Sequence of Events Appendix A. 1978, NAS8-32821, Martin Marietta

36. Electromagnetic Compatibility Control Plan for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

37. Material Usage List for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

38. TRS and ASE Verification Requirements and Specifications for Space Shuttle Program Teleoperator Retrieval System Volume I. 1978, NAS8-32821, Martin Marietta

39. TRS-AV-02 Volume I, Appendix B Assembly and Verification Subsystems and Systems Requirements and Specifications. 1978, NAS8-32821, Martin Marietta

40. TRS Verification Procedures Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

41. Prime Equipment Detail Specification Part I of Two Parts Performance, Design and Verification Requirements Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

42. GSE Identification Specification for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

43. TRS Instrumentation Program and Component List. 1978, NAS8-32821, Martin Marietta

44. Documentation, Specification and Drawing Tree for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

45. Electrical Cable Interconnect Diagrams, Schematics and Wiring List for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

46. Control System Stability and Dynamic Response for Space Shuttle Program Teleoperator Retrieval System Volume II. 1978, NAS8-32821, Martin Marietta

47. Control System Stability and Dynamic Response for Space Shuttle Program Teleoperator Retrieval System Volume I. 1978, NAS8-32821, Martin Marietta

48. Earth Orbital Teleoperator Systems Evaluation. 1978, NAS8-31848, Essex Corporation

49. Integrated Orbital Servicing Study, Volume I, Executive Summary. 1978, Martin Marietta

50. Teleoperator Retrieval System (TRS) Augmentation for Spacecraft Delivery and Retrieval, Design Summary. 1978, MSFC

51. Satellite Retrieval Study. 1978, Charles Stark Draper Laboratory, Inc.

52. TRS System Description Handbook for Space Shuttle Program Teleoperator Retrieval System. 1978, NAS8-32821, Martin Marietta

53. Low Energy Stage Study, Volume I, Executive Summary. 1978, NAS8-32710, Vought Corporation.

54. Assessment and Sensitivity Analysis of the Vought Corporation's Low Energy Stage Study. 1978, MSFC Program Development

55. Proximity-Vision System for Protoflight Manipulator Arm. 1978, H-30093B, National Bureau of Standards, for MSFC

56. Integrated Orbital Servicing Study. 1978, NAS8-30820, Martin Marietta

57. Orbital Servicer ServoDrive Console. 1978, NAS8-30820, Martin Marietta

58. One-G Orbital Servicer Operating Procedures. 1978, NAS8-30820, Martin Marietta

59. The Proto-Type Wrist Joint Assembly for the Triple Axis Common Pivot Arm Wrist (TACPAW). 1978, NAS8-31897, University of Nebraska

60. End Effector Device for Intermeshing Handling System. 1978, Pat. App. MFS-23962, MSFC - Clark

61. Integrated Orbital Servicing Study Follow-On. 1978, NAS8-30820, Martin Marietta

62. Earth Orbital Teleoperator Visual System Evaluation Program. 1977, NAS8-31848, Essex Corporation

63. Earth Orbital Teleoperator Manipulator System Evaluation Program. 1977, NAS8-31848, Essex Corporation

64. Earth Orbital Teleoperator Mobility System Evaluation Program. 1977, NAS8-31848, Essex Corporation

65. Manipulator System Performance Measurements, Mechanism and Machine Theory, 1977, Essex Corporation

66. Orbital Servicer Simulation Software Requirements. 1977, NAS8-30820, Martin Marietta

67. Engineering Test Unit and Controls. 1977, NAS8-30820, Martin Marietta

68. Extravehicular Activity Design Guidelines and Criteria. 1976, NAS8-31454, Essex Corporation

69. External Operations, Maintenance, and Repair (OMR) Mode Selection Criteria. 1976, NAS8-31454, Essex Corporation

70. Tug/SEPS/Free-Flying Payloads Simulation Demonstrations. 1976, NAS8-31454, Essex Corporation

71. Orbital Service Manipulators. 1976, NAS8-21812, Sperry Rand

72. Earth Orbital Teleoperator Systems and Concepts Analysis - Docking Retrieval Mechanism. 1976, NAS8-31290, Martin Marietta

73. Charged Induction Device for Teleoperator System. 1976, Tech Report, General Electric, for MSFC

74. Investigation of Technical Problems to Establish Design Specifications for a New Teleoperator Manipulator. 1976, NAS8-31897, University of Nebraska

75. A Method and Data for Video Monitor Sizing, Proceedings of the Sixth Congress of the International Ergonomics Association. 1976, Essex Corporation

76. Manipulator Evaluation Criteria, Proceedings of the Sixth Congress of the International Ergonomics Association. 1976, Essex Corporation

77. Earth Orbital Teleoperator Visual System Evaluation Program. 1976, NAS8-30545, Essex Corporation

78. Proto-Flight Manipulator Arm Assembly (EOTS). 1975, NAS8-31487, Martin Marietta

79. Earth Orbital Teleoperator Systems, Concepts and Analysis. 1975, NAS8-31290, Martin Marietta

80. Integrated Control/Display Station for Teleoperator and Experiments. 1975, NAS8-31147, Martin Marietta

81. Dual TV Display Unit for NASA/MSFC Teleoperator. 1975, Tech Report, General Electric

82. Manipulator System Performance Measurement, Proceedings of the Second National Conference on Remotely Manned Systems. 1975, Essex Corporation

83. Design Parameters for a Stereoptic Television System Based on Direct Vision Depth Perception Cues, Proceedings of the Nineteenth Annual Meeting of the Human Factors Society. 1975, Essex Corporation

84. Manipulator System Performance Evaluation: Some Problems and Approaches, Proceedings of the National Bureau of Standards Workshop on Performance Evaluation of Programmable Robots and Manipulators. 1975, Essex Corporation

85. A Study of Moving Base Simulation Motion Cues Utilizing Washout Technique, Proceedings of the Nineteenth Annual Meeting of the Human Factors Society. 1975, Essex Corporation

86. Role of Man in Flight Experiment Payloads - Phase II. 1975, NAS8-30953, Essex Corporation

87. Earth Orbital Teleoperator Manipulator System Evaluation Program, Report Number 3. 1975, NAS8-30545, Essex Corporation

88. Earth Orbital Teleoperator Manipulator System Evaluation Program, Report Number 2. 1975, NAS8-30545, Essex Corporation

89. A Study of Payload Specialist Station Monitor Size Constraints. 1975, NAS8-30545, Essex Corporation.

90. Optical Range and Range Estimation for Teleoperator Systems, Proceedings of the Eighteenth Annual Meeting of the Human Factors Society. 1974, Essex Corporation.

91. Manipulator System Man-Machine Interface Evaluation Program, Report Number H-4-3. 1974, NAS8-28298, Essex Corporation

92. Earth Orbital Teleoperator System Man-Machine Interface Evaluation, Report Number H-4-1. 1974, NAS8-28298, Essex Corporation

93. Earth Orbital Teleoperator Visual System Evaluation, Tset Report Number H-4-2. 1974, NAS8-28298, Essex Corporation

94. Teleoperator Equations of Motion. 1974, NAS8-29632, University of Tennessee

95. The Application of Image Enhancement Techniques to Remote Manipulator Operations. 1974, NAS8-29271, University of Tennessee

96. Modal Analysis and Control of Flexible Manipulator Arms. 1974, NAS8-28055, Massachusetts Institute of Technology

97. Use of the Link Six DOF Motion Platform as Part of a Docking Hardware Simulation/Test Bed Facility. 1974, Computer Sciences Corporation, for MSFC

98. General Purpose Simulation at Marshall Space Flight Center. 1974, AIAA

99. Equipment Specifications for Manipulator Assembly of Remotely Operated Systems. 1974, NASA, MSFC-SPEC-50M23186

100. Teleoperator Docking Simulation. 1974, NAS8-28298, Essex Corporation

101. Role of Man in Flight Experiment Payloads - Phase I. 1974, NAS8-29917, Essex Corporation

102. Man-Systems Evaluation of Moving Base Vehicle Simulation Motion Cues. 1974, NAS8-29914, Essex Corporation

103. Typical Teleoperator Time Delay Profiles Phase II Final Report. 1974, NAS8-30919, Martin Marietta

104. Free Flying Teleoperator Breadboard Vehicle. 1973, MSFC S&E-ASTR, WP 7-73

105. Conceptual Design Study for A Teleoperator Visual System. 1973, NAS8-29024, Martin Marietta

106. Shuttle Free Flying Teleoperator System Experiment Definition. 1973, NAS8-27895, Bell Aerospace

107. Shuttle Remote Manned Systems Requirements Analysis. 1973, NAS8-29904, Martin Marietta

108. Recovery of Spinning Satellites. 1973, NAS8-29627, Northrop

109. A Study of Space Manipulator Motors. 1973, MSFC-TM-758, Sperry Rand

110. Design of A Terminal Pointer Hand Controller for Teleoperator Applications. 1973, NAS8-28760, URS/Matrix

111. SD-2 Hand Controller for Teleoperator Manipulators. 1973, NAS8-29724, Massachusetts Institute of Technology

112. Technical Memorandum Teleoperator Grappler Circuit Development. 1973, MSFC-TM-659, Sperry Rand

113. Advanced Action Manipulator System (ADAMS). 1973, NAS8-22022, General Electric

114. Shuttle Free Flying Teleoperator System Experiment Definition. 1973, NAS8-29153, Bell Aerospace

115. Human Factor Roles in Design of Teleoperator Systems, Proceedings of the 17th Annual Meeting of the Human Factors Society. 1973, Essex Corporation

116. The Applications of the Remote Control of the Manipulator in Manned Space Exploration. Paper presented at the Robot and Manipulator Symposium (ROMANSY). 1973

117. The Role of Man in Flight Experiment Payload Missions. 1973, NASW-2389, Essex Corporation

118. Some Effects of Transmission Parameters on Detection and Recognition of Television Images, Proceedings of the Seventeenth Meeting of the Human Factors Society. 1973, Essex Corporation

119. Earth Orbital Teleoperator Visual System Evaluation Program, Report 1. 1973, NAS8-28298, Essex Corporation

120. Shuttle Free Flying Teleoperator System Experiment Definition. 1972, NAS8-27895, Bell Aerospace

121. Evaluation of Human Operator Visual Performance Capability for Teleoperator Missions, Remotely Manned Systems, Proceedings of the First National Conference on Teleoperators. 1972, Essex Corporation.

122. Baseline Tug Definition Document. 1972, MSFC Preliminary Design Office

123. Teleoperator Technology and System Development. 1972, NAS8-27021, Bell Aerospace

124. A Study of Teleoeprator Systems Performance Requirements. 1972, NAS8-27013, URS/Matrix

125. Conceptual Design Study for a Teleoperator Visual System. 1972, NAS8-29024, Martin Marietta

126. Rancho Anthropomorphic Manipulator (RAM) Final Report. 1972, NAS8-28361, Rancho Los Amigos Hospital

127. Preliminary System Design Criteria for FFTO Satellite Retrieval Mission. 1972, NAS8-27021, Bell Aerospace

128. Report on Earth Orbital Teleoperator Visual System Evaluation. 1972, NAS8-28298, Essex Corporation

129. Free Flying Teleoperator Mission Analysis. 1972; NAS8-28298, Essex Corporation

130. Teleoperators and EVA for Shuttle Missions. Paper presented to the AAAS and ASA Conference on Shuttle Payloads. 1972

131. Man-Machine Interface for Controllers and End Effectors, Remotely Manned Systems, Proceedings of the First National Conference on Teleoperators. 1972, Essex Corporation

132. Teleoperator Man-Machine Interface Requirements and Concepts for Satellite Retrieval and Servicing. 1972, NASW-2220, Essex Corporation

133. Teleoperator Systems Human Factors Program. 1971, NASW-2175, Essex Corporation

134. Remote Control and Navigation Tests for Application to Long Range Surface Exploration. 1971, MSFC - Vinz, TMX 64621

135. Advanced Action Manipulator System (ADAMS). 1971, NAS8-26377, General Electric

136. Selection of Systems to Perform Extravehicular Activity - Man and Manipulator. 1970, NAS8-24384, URS/Matrix

137. Dual Mode Manned/Automated Lunar Roving Vehicle Design Definition Study. 1970, NAS8-24528, Bendix Aerospace

138. Dual Mode Lunar Roving Vehicle. 1970, NAS8-24529, Grumman Aerospace

139. Dual Mode Lunar Roving Vehicle Navigation Systems. 1970, NAS8-24858, University of Tennessee

140. Advancements in Teleoperator Systems. 1969, NASA, SP-5081, University of Denver

141. Teleoperator Controls. 1968, NASA, SP-5070

142. Teleoperators and Human Augmentation. 1967, NASA, SP-5047

143. Independent Manned Manipulator Summary Technical Report. 1966, Report 00.859, Ling-Temco-Vought

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National Aeronautics and
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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

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Reply to Attn of: EC13 (56-82)

MAY 24 1982

TO: Distribution

FROM: EC01/Mr. Wojtalik

SUBJECT: Chronological Summary of Teleoperator Activities From 1971 to 1981

Enclosed are copies of a chronological summary of teleoperator simulation activities that have taken place within the Information and Electronic Systems Laboratory.

These documents have been assembled from contractor year-end reports, contracted study reports and internally generated documentation.

These documents were assembled to provide those individuals that are involved in teleoperation and robotics an insight into this laboratory's activities in teleoperation research for the past 11 years.

Any comments or requests for additional information should be directed to E. G. Guerin, MSFC/EC13, FTS (872-4634) (205) 453-4634.

Fred S. Wojtalik
Director, Information and
Electronic Systems Laboratory

Enclosures

Mr. Joseph Engelberger, President
Unimotion, Inc.
Shelter Rock Lane
Danbury, CT 06801

Dr. Ewald Heer
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103

Prof. W. R. Ferrell
Systems & Industrial Engineering
University of Arizona
Tucson, AZ 85711

Dr. James Albus
National Bureau of Standards
Washington, DC 20234

Mr. George Smith
Martin Marietta Corporation
Denver, CO 80202

Mr. Richard E. Hohn
Cincinnati Milacron
4701 Marburg Avenue
Cincinnati, Ohio 45209

Dr. Thomas Sheridan
Mass. Institute of Technology
Cambridge, MA

Dr. Ron Larson
NASA Headquarters
Washington, DC 20234

Dr. Margaret Clarke
ORAU, P.O. Box 117
Oak Ridge, TN 37830

Dr. R. J. Hung
UAH/Mechanical Engineering
Huntsville, AL 35899

Dr. Ross L. Pepper
NOSC, Hawaii Laboratory
P.O. Box 997
Kailua, Hawaii 96734

Mr. Robert Wernli
NOSC, Ocean Technology Dept.
San Diego, CA 92152

Prof. Bernard Roth
Mechanical Engineering Dept.
Stanford University
Stanford, CA 94305

Mr. Bernard M. Sailott
Executive Director, RIA
One SME Drive
P.O. Box 930 Dearborn, MI 48128

Director, Engineering Psychology
Programs, Code 455
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director, Cybernetics
Technology Office, Advanced
Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

Director, Information Systems
Program, Code 437
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

Director, Naval Research
Laboratory, Technical Information
Division
Code 2627
Washington, D.C. 20375

Commander, Naval Facilities
Engineering Command
R&D Plans & Programs Division
Code 031A
Alexandria, VA 22322

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Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, MD 20014

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Engineering Branch
Submarine Medical Research Laboratory
Naval Submarine Base
Groton, CT 06340

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Warminster, PA 18950

Director, Human Factors
Engineering Branch
Code 1226
Pacific Missile Test Center
Point Mugu, CA 93042

Human Factors Department
Code N215
Naval Training Equipment Center
Orlando, FL 32813

Technical Director, U.S. Army
Human Engineering Labs.
Aberdeen, MD 21005

Director, Human Engineering Division
Aerospace Medical Research Lab.
Wright Patterson AFB, OH 45433

Mr. Alan J. Pesch
Eclectech Associates, Inc.
P. O. Box 179
N. Stonington, CT 06359

Guest Associates, Sue Lucas
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Aerospace/R. Broussard
Aerospace/E. Mayfiend

SPAR Aerospace Ltd.
Toronto, Canada/C. Butts

JSC/SA12/Richard Hergert
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