

Contract NAS 9-11943
DRL T-350
Line Item 4
MSC 05219
MB-R-71/105

CR 115481

FINAL REPORT

A SHUTTLE AND SPACE STATION MANIPULATOR SYSTEM
FOR
ASSEMBLY, DOCKING, MAINTENANCE, CARGO HANDLING
AND SPACECRAFT RETRIEVAL
(PRELIMINARY DESIGN)

Volume II - Concept Development and Selection

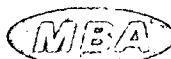
7 January 1972

Prepared For:

National Aeronautical and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

OFFICE OF PRIME RESPONSIBILITY

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(NASA-CR-115481) A SHUTTLE AND SPACE
STATION MANIPULATOR SYSTEM FOR ASSEMBLY,
DOCKING, MAINTENANCE, CARGO HANDLING AND
SPACECRAFT RETRIEVAL (PRELIMINARY (MB
Associates) 7 Jan. 1972 194 p CACL 22B G3/31

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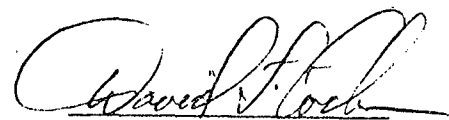
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FOREWORD

This final report presents the results of a four-month preliminary design study performed by MBAAssociates under contract to NASA Manned Spacecraft Center (MSC). Mr. Richard Davidson was the MSC Program Technical Manager, Mr. Donald F. Adamski, the MBA Program Manager and Mr. James Cooper, the MBA Project Engineer. MBAAssociates was the overall system designer and integrator. Perceptronics, Inc. and Control Data Corporation, under subcontract to MBA, were responsible for man-machine interface, supervisory computer control system and head-aimed foveal TV system support, respectively. Hamilton Standard Division, United Aircraft and Garrett Corporation, AiResearch Manufacturing Division contributed generously of their time to provide technical support and background information on environmental control, life support and power supply systems. In addition, MBA consultants, Messrs. Kentner Wilson, Carl Flatau, Robert Rumble and Dr. William Gerberich contributed significantly to this effort.

The study was divided into two phases. Phase 1 consisted of concepts development and selection. Phase 2 consisted of further analyses and refinement of the design selected in Phase 1 and of simulation studies in certain critical control and viewing system areas.

The Final Report consists of four volumes as follows:

- Volume I - Management Summary
- Volume II - Concept Development and Selection
- Volume III - Concept Analysis
 - (Part I - Technical)
 - (Part II - Estimated Development Program)
- Volume IV - Simulation Studies

A detailed presentation to NASA MSC on concepts development and selection was given at Houston, Texas on 30 August 1971. Presentation Aids for that briefing are given in MBA Document MB-R-71/85. Volume II of this Final Report does not present all of the information given at the briefing, but instead summarizes all of the important elements of that briefing. Similarly, a final report summary presentation to NASA MSC was given by MBA at Houston, Texas on 3 December 1971. Presentation Aids for that briefing are given in MBA Document MB-R-71/107. Volume III contains all of the information presented at the final report briefing, including a description of the final preliminary design and the design analyses and tradeoff studies leading to finalization of the design.

ABSTRACT

A preliminary design has been established for a general purpose manipulator system suitable for docking, cargo handling, assembly and maintenance operations in support of space shuttle and space station missions. The manipulator can be used interchangeably on the shuttle and station and can be transferred back and forth between them. Control of the manipulator is accomplished by hard wiring from internal control stations in the shuttle or station. A variety of shuttle and station manipulator operations have been considered including servicing the Large Space Telescope; however emphasis has been placed on unloading modules from the shuttle and assembling the space station. Simulation studies on foveal stereoscopic viewing and manipulator supervisory computer control have been accomplished to investigate the feasibility of their use in the manipulator system.

The basic manipulator system consists of a single 18.3m (60') long, 7 degree of freedom (DOF), electrically actuated main boom with an auxiliary 3 DOF electrically actuated, extendible 18.3m (60') maximum length, lighting and viewing boom. A 3 DOF orienter assembly is located at the tip of the viewing boom to provide camera pan, tilt and roll. Primary viewing is accomplished with a black and white and color stereoscopic, foveal, zoomable TV system. Direct viewing is used as a backup where possible. TV cameras and lights are mounted on the main boom, the auxiliary boom and on the space station and shuttle. The main boom can exert a tip force of 111 Newtons (25 lbs) at which a tip deflection of 0.142m (5.6") occurs for the boom fully extended (straight out). The main boom actuators incorporate slip clutches to prevent actuator/boom overloads. The main boom is symmetrical about the elbow and consists of two 8.15m (27') long arms each having identical 3 DOF, 1m (3.29') long wrist assemblies. The boom can be operated from either end and is capable of walking end-over-end from one root point to another. Root points are located strategically about the station and shuttle so that the desired working envelopes can be accessed for cargo handling assembly, repair and maintenance.

The end connectors on the main boom plug directly into the root points so that no special end effectors are required for station assembly and cargo handling operations. The basic manipulator system weighs approximately 421 kgms (930 lbs). Additional boom and general purpose and/or special purpose end effectors can be added as required for other operations. A preliminary program estimate has been made for development and flight qualification of the manipulator system, including a dexterous general purpose end effector and including ground simulations, and operator training up to, but not including, orbital flights.

The results of this preliminary design study are presented in four volumes as follows:

- Volume I - Management Summary
- Volume II - Concept Development and Selection
- Volume III - Concept Analysis
 - (Part I - Technical)
 - (Part II - Estimated Development Program)
- Volume IV - Simulation Studies

Volume II describes the various concepts considered and the rationale for the selected design. Volume III describes the selected preliminary design and the supporting design and tradeoff analyses.

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1.0 DEFINITIONS

Analog to Digital Converter (A/D) - An electronic device to convert a continuous electronic analog signal to a pulsed digital signal with the successive bit positions representing increased weighting of the output value.

Anthropomorphic - Having human form or with human attributes, specifically in this case, geometrically similar to a human to enable a position-position force reflecting dexterous control.

Berthing - The process of connecting two bodies as in docking, but with the assistance of a manipulator mechanism to accurately position the bodies and to attenuate the docking load by absorbing the kinetic energy of closure rate.

Boom - The multijointed, articulated, structural, load carrying assembly of the teleoperator (manipulator) system.

Coder - An electronic device to develop a pulse coded address for transmission of data on a data bus.

Connector - The tip of the teleoperator boom that inserts into and latches to the root points and end effectors.

CRT - Cathode ray tube

Data Bus - An electronic system for transmission of data to a number of addresses by pulse coding the addresses and data on a common wire bus.

Docking - The process of connecting two orbiting bodies rigidly together by use of the attitude control/propulsion systems of the active body to close on the passive body and to accurately engage the docking mechanism which consists of a centering mechanism, a docking load attenuation mechanism and a latch.

Decoder - An electronic device to decode a pulse coded address from a data bus and to enable transmission of data.

Digital to Analog Converter (D/A) - An electronic device to convert a pulsed digital signal to a continuous electronic analog signal.

DOF (Degrees of Freedom) - A characteristic of a positioning system which defines the number of independent variables required to describe its motion/configuration. DOF is equal to the number of active joints in the system and does not include so called "indexing joints" unless so specified.

End Effector - A special purpose attachment to the boom to enable dexterous or special tasks to be accomplished. May be a simple attachment, but can be complicated as with the anthropomorphic end effector.

EC/LSS - Environmental Control/Life Support Systems.

Foveal (Eye Acuity Matching) - A split field viewing system with a small center field of high resolution and a large, wide angle peripheral field of low resolution approximating the acuity distribution of the eye.

Manipulator - An articulated, multijointed device for grasping, maneuvering, moving and otherwise performing operations on objects. A manipulator may resemble a teleoperator in its construction, but unlike the teleoperator does not always (and in fact may never) require man as an active element in the control system. Manipulator has been used interchangeably with teleoperator in this report.

Mating - The process of matching the teleoperator end location and orientation to that of the mating socket on the object to be moved, and inserting and latching the tip.

NAT - The man-size electro-hydraulic-pneumatic Naval Anthropomorphic Teleoperator being developed by MBA with Navy funding administered by AEC/NASA SNSO under Contract SNPN-53.

PCM - Pulse coded modulation -system of data transmission.

PWM - Pulse width modulation - efficient power amplification method.

Root Point - The socket on the host body or vehicle from which the teleoperator is operated. The root point is both structural, supporting reaction forces on the vehicle structure and connective transmitting power and control signals to the teleoperator.

SOW - Contract Statement of Work.

Stereo-Foveal - A split field viewing system with a small stereoscopic center field (foveal) of high resolution and a monocular peripheral field of low resolution.

Teleoperator (T/O) - A general purpose, dexterous, man-machine system that can augment man by projecting his manipulatory, pedipulatory and sensory capabilities across distance and through physical barriers into hostile environments. Man is actively involved as a part of the control loop in a Teleoperator System. Teleoperator has been used interchangeably with manipulator in this report.

$v_{in}(t)$	The electronic input drive to the control system
V_m	Terminal voltage of the motor
m	Mass of the load
x	Linear displacement variable
K_s	Spring constant of the boom
l	Length of the boom
θ	Angular displacement variable
k_v	Velocity coefficient
k_n	Motor speed constant
I	Motor current
R	Motor armature resistance
T	Motor torque
k_T	Torque constant
s	Laplace variable
ω_n	Natural resonant frequency - $\omega = 2\pi f$
ζ	Damping coefficient
$u_{-1}(t)$	Unit step function
$G(s)$	Transfer function
$X(s)$	Frequency domain output variable
$V_{in}(s)$	Frequency domain input variable
τ	Shear stress-Pascal or Newton/m ² (psi)
σ	Stress-Pascal or Newton/m ² (psi)
P	Tip force - kg (lb)
M	Moment -Newton meters (ft lb)
L	Boom length - meters (ft)
r_{ave}	Average radius of boom tube - cm (in)
d	Diameter of boom - cm (in)
T	Torque - Newton meters (ft lb)
I	Cross section moment of inertia

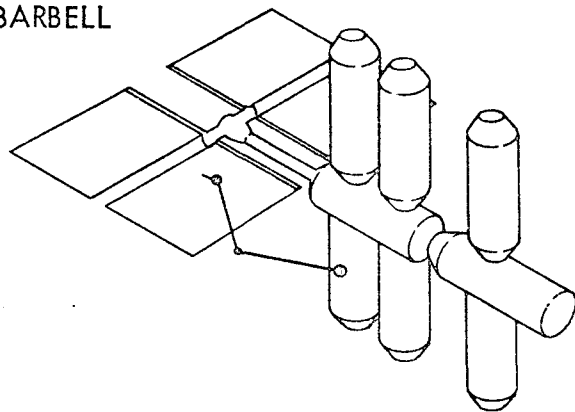
2.0 SUMMARY

The initial objective of this study was to establish a preliminary design for a space station assembly and cargo handling manipulator system having its own manned control module. The space station would be assembled from, and cargo carried in, modules which would be transported into orbit in the cargo bay of the shuttle. The complete manipulator system was also to be capable of stowage and transport in the shuttle cargo bay. The basic functions of the manipulator were to be docking and assembly of the modules onto a station core, cargo docking or cargo transfer to the completed station. Other functions such as propulsion package replacement and maintenance were to be considered, provided they did not impact the basic station or manipulator system design.

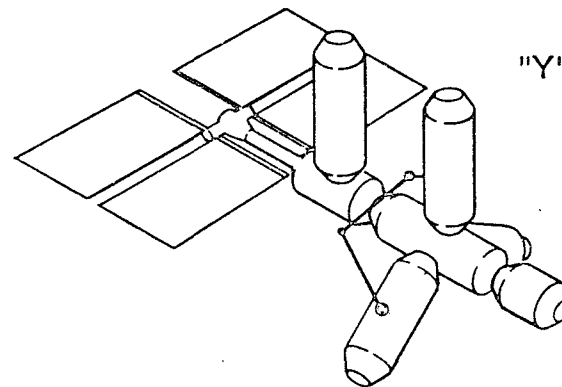
One or more booms could be considered for the manipulator system, however, no force levels or task times were specified. No manipulator system weight limit was given for the concept selection phase, however, as with all aerospace equipment minimum weight must be optimized together with development, fabrication and operational complexity and cost. The manipulator control module was to have its own environmental control, life support and power systems capable of limited operation independent of the station, although normally the module could utilize the station utilities.

Several space station configurations were considered as shown in Figure 2-1. The cruciform configuration was selected as the reference for this study. Several shuttle configurations were considered during the concept selection phase. Shuttle details were not important except that the cargo bay was taken to be 4.57 m (15') in diameter by 18.3m (60') in length and that the station module could be berthed to a berthing port on the top of the shuttle just forward of the cargo bay. Parameters for both the space station and shuttle are summarized in Appendix B.

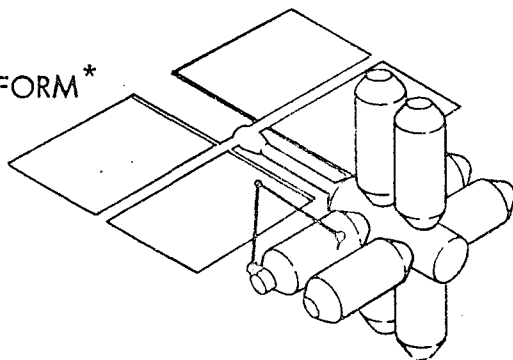
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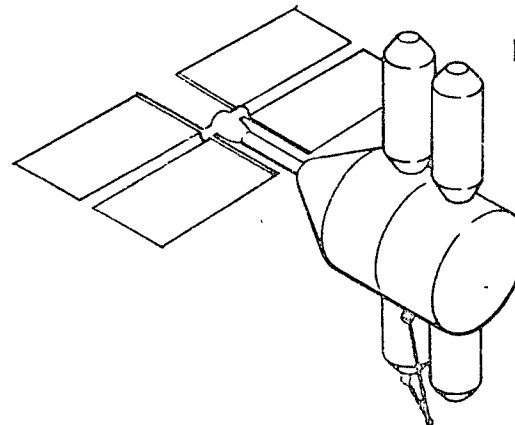
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CRUCIFORM*



LARGE CAN



* Selected Reference Station

FIGURE 2-1.
SPACE STATION CONFIGURATIONS



As the concept selection study progressed, it became apparent that considerable overall economies in the development of space manipulators could be achieved by designing a general purpose manipulator system suitable for both space station and shuttle based operations. The potential commonality between the station and shuttle application is as follows:

<u>Common Elements</u>	<u>Different Elements</u>
Manipulator Booms	Crew Capsule
General Purpose End Effectors	ECS/LSS
Control and Display	Emergency Systems
Data Processing	Special Purpose End Effectors
Telemetry	
Dedicated Computers	
Control Station Design	

In order to achieve the above commonality, it is only necessary that the manipulator booms be literally interchangeable and that the man/machine interface (controls and displays) be sized to fit in both the station and shuttle.

The evolution of the recommended manipulator system concept is illustrated by the concept selection networks shown in Figures 2-2 through 2-6. The boom configuration selection is shown in Figure 2-2. One boom was selected because of the simpler control requirements (lower cost and higher reliability) and because each boom would have to be equally strong; i. e., if one failed, the other would be required to absorb the loads formerly shared by two booms. Furthermore, it appeared that all of the required space station tasks could readily be accomplished with one boom. Primary emphasis was placed on the station in Phase 1. A fixed length elbow configuration was selected because it appeared simpler than an extensible boom, it could be made stronger for the same weight expenditure and the extensible feature was not required to avoid obstacles or achieve access throughout the desired working envelope. A boom symmetrical about the elbow was selected because of the desired interchangeability between the station and shuttle. A constant section, circular tube type construction was selected because of the nature of the loads imposed on the boom.

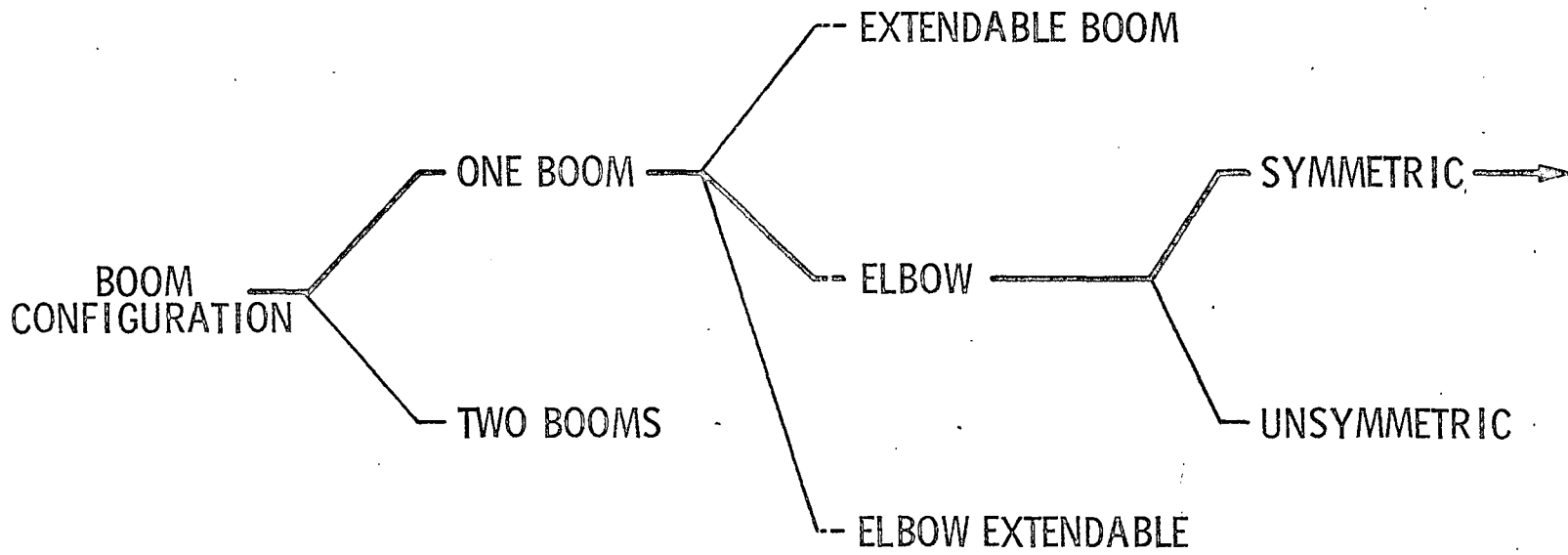
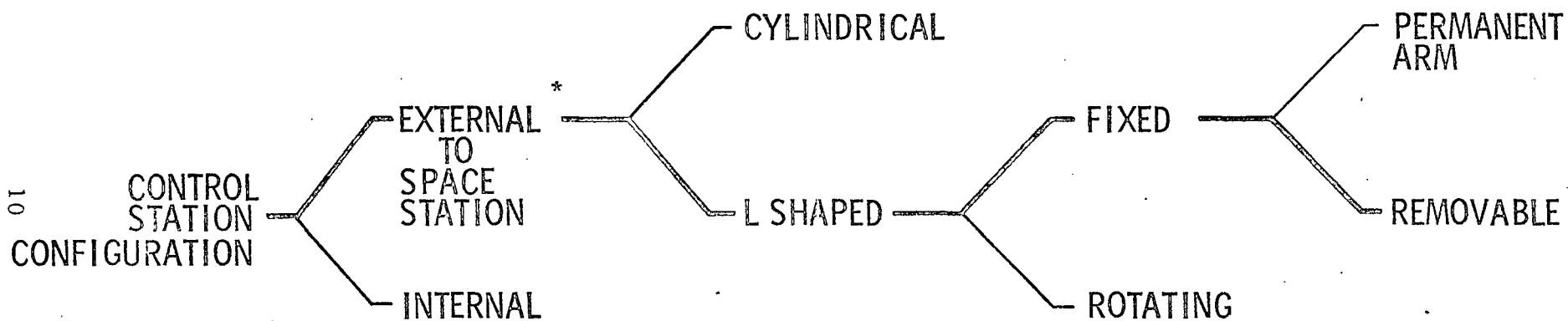


FIGURE 2-2.
BOOM CONCEPT SELECTION NETWORK

It was a contract requirement that a separate, external, manned manipulator module (control station) be used for the space station assembly and cargo handling system in order to enhance direct viewing. The external control station selection is shown in Figure 2.3. An L-shaped module was selected because of the increased direct viewing achieved by having the crew compartment located radially away from a station module longitudinal axis. (For example, if mounted on the end of a side module, the operator could see along the sides of the module to which he was mounted.) A "fixed" module was selected to avoid the problems of a rotating pressure seal, however, the module could be oriented in at least opposite (180°) positions. A removable boom was selected because of the desired interchangeability between the station and shuttle and to facilitate maintenance of the manipulator system. (A new boom could be brought up to replace a damaged or malfunctioning boom rather than attempt in-orbit repair.)

Detailed consideration of the desired station/shuttle commonality and interchangeability and of station manipulator mobility requirements led to MBA's recommendation of a unique walking boom which could be operated from either an internal or external control station. It is a far simpler task to walk the boom end-over-end from one root point to another than to move the relatively large control module from one berthing port to another. Furthermore, removing man from the transfer reduces the safety problems and greatly simplifies the procedures, support equipment and root point utility requirements. The viewing system is not compromised by the walking boom concept since direct viewing is not possible nor adequate for many tasks; for example, repair or maintenance tasks using a dexterous end effector. Thus a high quality indirect viewing system is still required for a "direct" viewing system.



* Contract Requirement

2401 9330



FIGURE 2-3.
CONTROL STATION CONCEPT SELECTION NETWORK

The control concept selection is shown in Figure 2-4. The length of the boom coupled with the requirement for low weight while moving or berthing massive objects [11,340 kgms (25,000 lb) to 129,118 kgms (284,659 lbs)] necessitates limited tip velocities [$\leq .61$ m/sec (2 fps)] and low angular rates ($\leq 3^\circ$ /sec). It is not practical (or perhaps even possible) to use a conventional position-position geometrically similar master slave controller for such operations. The size ratio (slave/master) of $\sim 20/1$ would amplify all operator perturbations causing dynamic problems on the slave and extreme operator fatigue would occur because of the slow steady motion required. A computer aided control system was selected to preclude these difficulties. A library of preprogrammed motions would be available and new motions for gross translation, deceleration, etc. could be inputted to the computer by means of a small, scale model, geometrically similar boom. The computer would optimize the desired motions and drive the manipulator boom in a smooth proportional rate control mode. Position-position and position-position with force feedback are not appropriate to such a computer driven control mode and fixed rate control is not as desirable nor is it necessary. After the boom is brought to the desired "near proximity" configuration (by the above computer aided control), and end point combined force to rate and position-position control mode was selected for final berthing, capture or other precision operations. The precision operation would still be interfaced by the computer, but the operator would be controlling in real time the end point location by force to rate control and the end point orientation (wrist) by position-position control. The computer would make the necessary coordinate transformations and drive the boom in such a way so as to present the operator with an x-y-z coordinate system referenced to his working field of view. Selection of the combined force to rate and position-position control mode provides the operator with a single analog, proportional controller. Control of a small (man like) dexterous end effector would be by a bilateral, position-position force feedback control system.

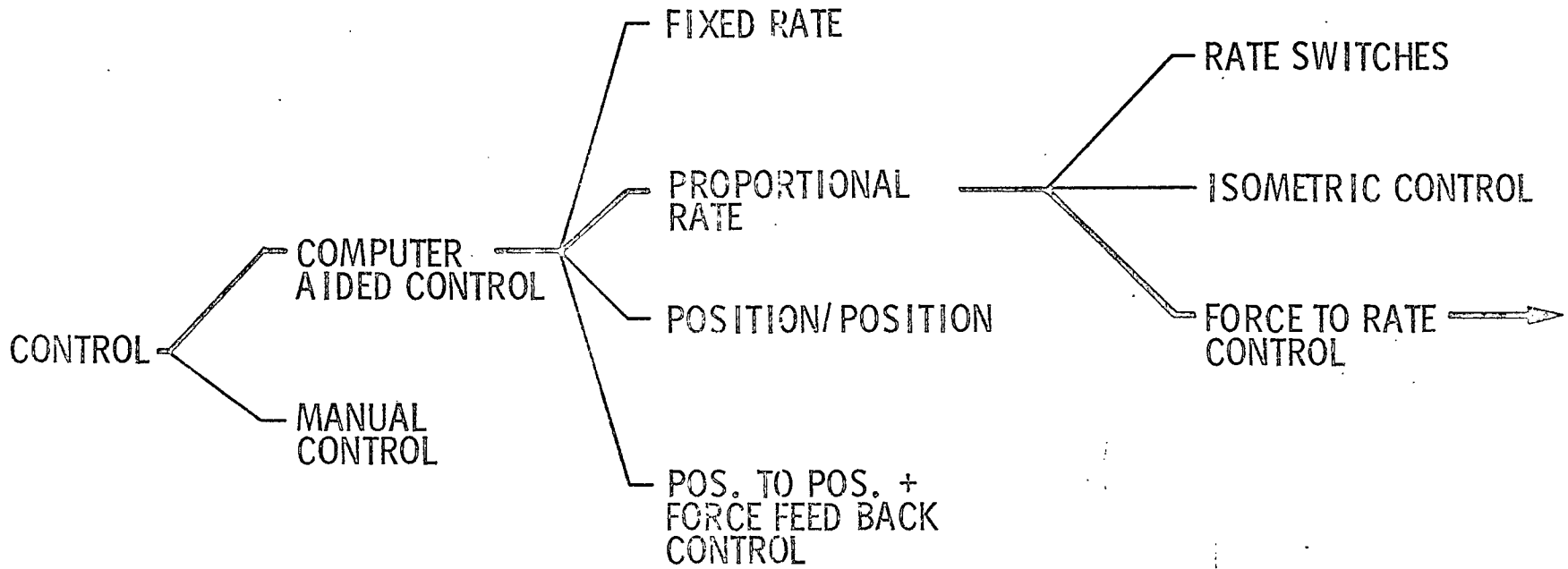


FIGURE 2-4.
CONTROL CONCEPT SELECTION NETWORK



The viewing system concept selection is shown in Figure 2-5. TV (black and white plus color) and direct viewing were selected to achieve maximum flexibility and capability. A stereoscopic foveal system was selected to provide the overall field-of-view required for general orientation and coordination and the detail (resolution) and depth perception required for precise tasks while at the same time minimizing the data processing and transmission bandwidth requirements. A mobile viewer was selected because it could be made of off-the-shelf components (low cost), it would offer high quality optical images, it could be made light weight compared with panel displays and the camera field-of-view could be controlled by a natural head activated control system. (The disadvantage of the viewer is that the operator must place his face onto a viewing hood and is thereby somewhat encumbered.) The position-isometric activation concept was selected because within a limited range (small head motion), the camera field-of-view could be controlled in a natural position-position mode. For greater camera movement, the mobile viewer would be pressed isometrically at the limit of the position-position travel in the desired direction to control the camera in a rate mode. Both earth shadow and sunlight fill-in illumination concepts were required. The dynamic range available with current cameras is large enough to accommodate low intensity to bright sunlight conditions; however, they cannot accommodate two extremes simultaneously. Thus low intensity [10 to 20 watts/ m^2 ($\sim 1-2$ watts/ ft^2)] lamps were selected for earth shadow conditions. Field separation by means of the two camera foveal concept was selected over the sun cheater [line spectrum illumination @ 100 - 200 watts/ m^2 ($\sim 10-20$ watts/ ft^2)] or mirror reflection because it requires no additional equipment or illumination. Large contrast lighting conditions are not important in the largest field of view, hence fill-in is not required there. The smaller foveal area of interest can be viewed under its own local lighting conditions independent of the overall lighting conditions. Although not shown on Figure 2-5, a separate dedicated boom was selected for supporting, locating and controlling additional lights and viewing cameras.

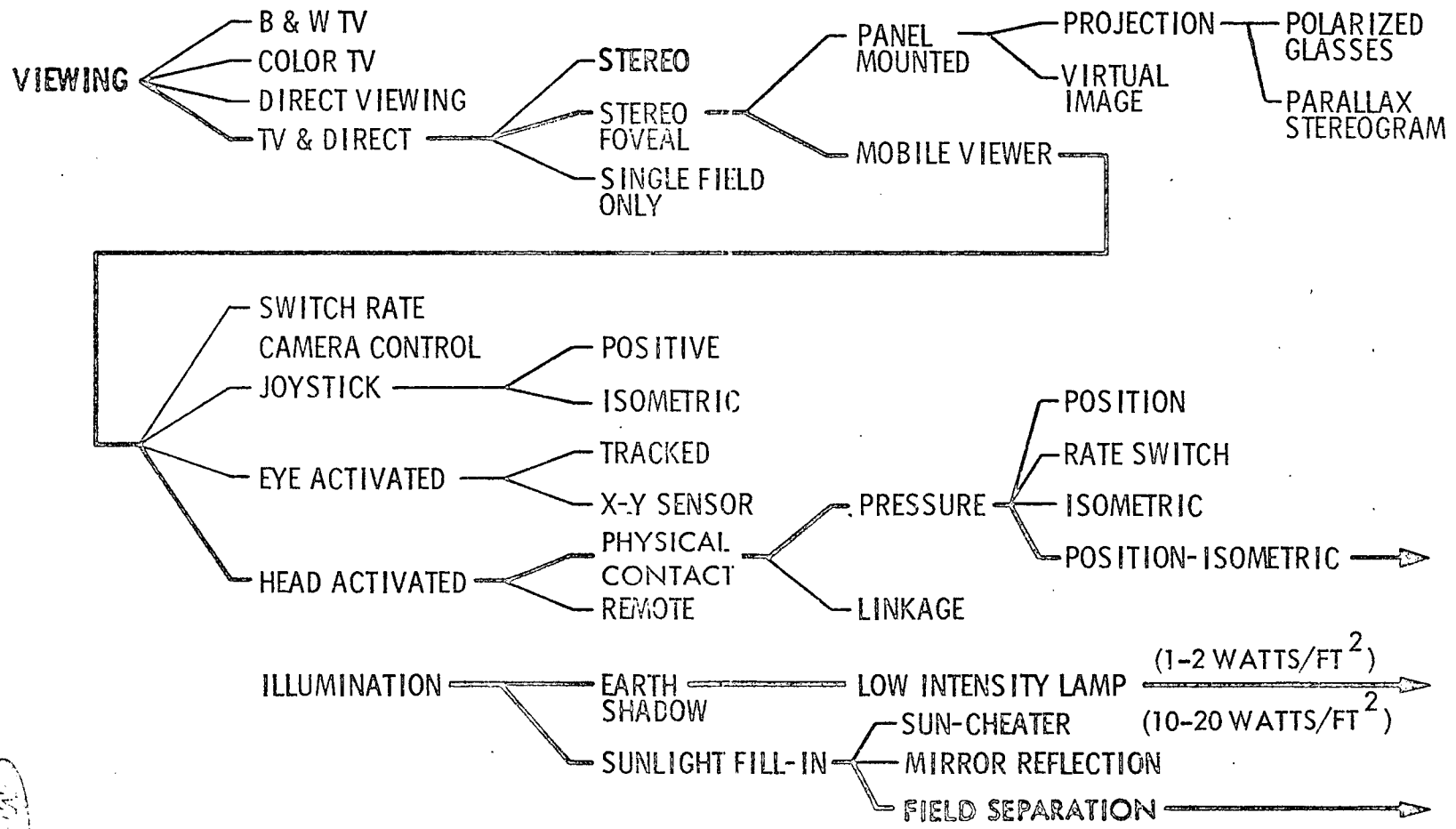


FIGURE 2-5.
VIEWING SYSTEM CONCEPT SELECTION NETWORK



The environmental control, life support and power system selection is shown in Figure 2-6. It was a requirement that the manned control module be capable of limited independent operation; however, it is clearly desirable to utilize the station or shuttle utilities where possible. Therefore, a dual EC/LSS concept was selected. The open loop system and open loop emergency equipment selections refer to the separate module and operator emergency escape systems respectively. Open loops were selected for these systems because for the limited times (~30 minutes) required, open loop systems are lighter and less costly. About 5 hours of independent operating time were required for the complete manned control module. For the required average operating power of ≤ 3.4 kw secondary batteries are the logical choice for the main and backup power sources.

A manipulator system using the external control module without a walking boom but incorporating all of the other above concept selections is illustrated in Figure 2-7. The manipulator system recommended by MBA is illustrated in Figure 2-8. It utilizes the walking boom concept and can be operated from either an external or internal control station. A small internal portable control station which can plug into a berthing post was also recommended. This station would be used at the port to which a module was being berthed so that direct head-on viewing of the berthing could be used without need of TV displays. Note that the walking boom concept operated from an internal control station requires no capability for independent operation detached from the station or shuttle and since the operator is inside the station or shuttle no separate environmental control or life support systems are required. The above rationale backed up with greater detail on all of the concepts considered was presented by MBA in a briefing to MSC and other NASA personnel on August 30, 1971. MSC approved and authorized MBA to proceed with the recommended concept with the following options selected:

- 1) An internal control station without direct viewing shall be used.
- 2) A panel display shall be used rather than a mobile viewer so as not to encumber the operator.

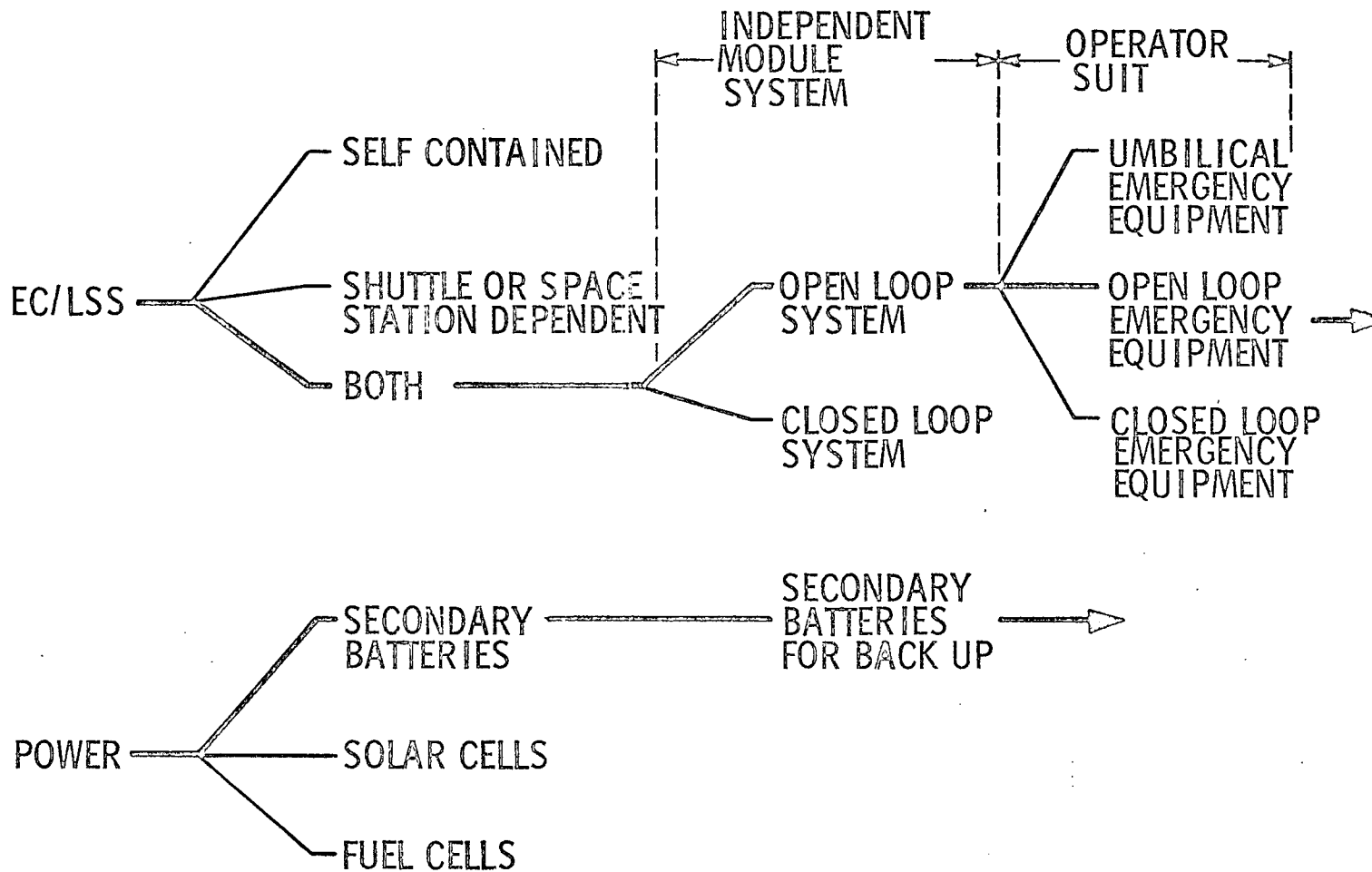
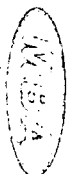
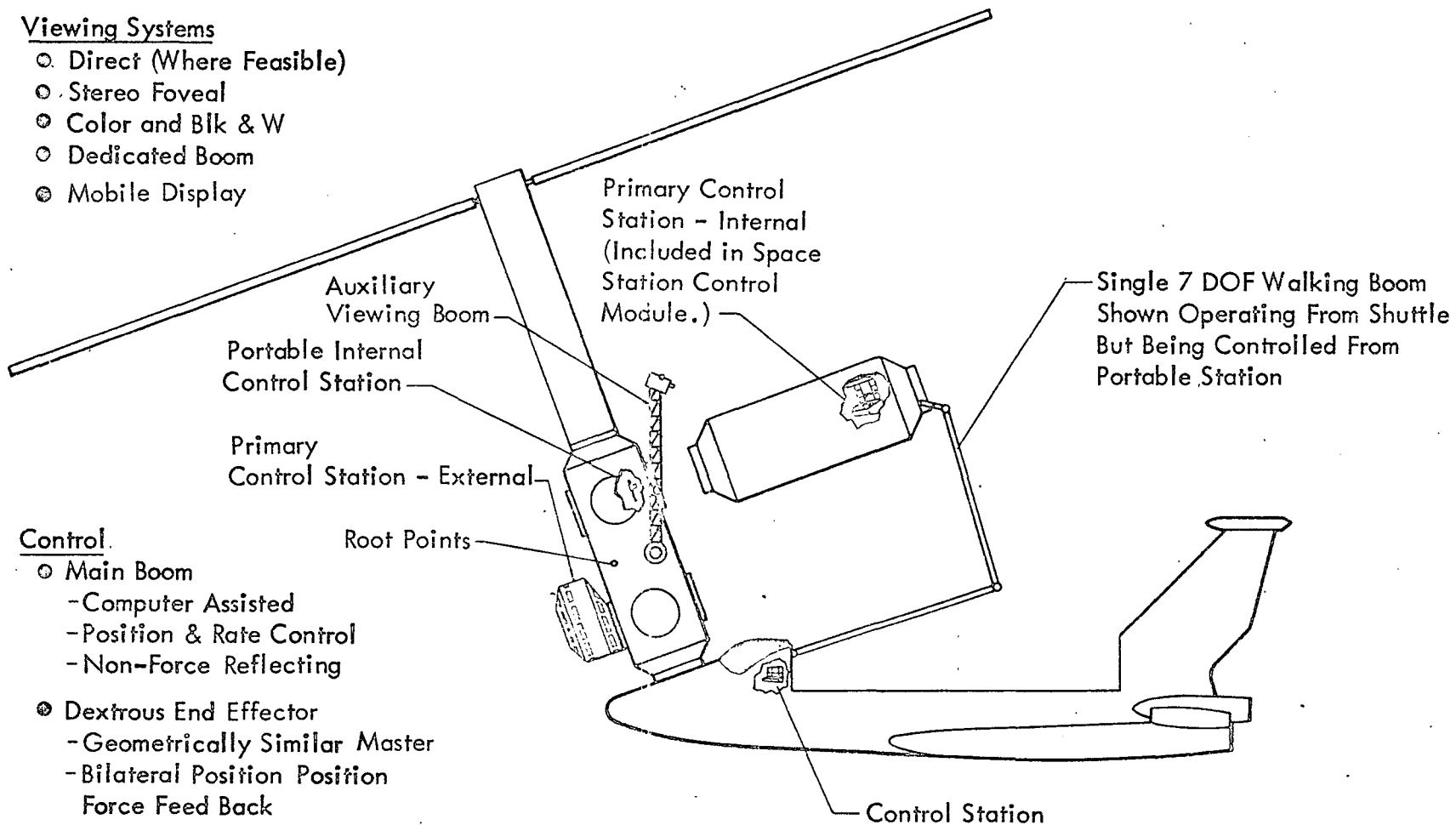


FIGURE 2-6. ENVIRONMENTAL CONTROL LIFE SUPPORT AND POWER SUPPLY SYSTEMS CONCEPT SELECTION NETWORK



Viewing Systems

- Direct (Where Feasible)
- Stereo Foveal
- Color and Blk & W
- Dedicated Boom
- Mobile Display



Control

- Main Boom
 - Computer Assisted
 - Position & Rate Control
 - Non-Force Reflecting
- Dexterous End Effector
 - Geometrically Similar Master
 - Bilateral Position Position
 - Force Feed Back

Telecommunications

- State Of The Art
- Hard Wired

FIGURE 2-7.
RECOMMENDED PHASE I MANIPULATOR SYSTEM CONCEPT
WITH CONTROL STATION OPTIONS



- 3) No portable control stations are to be used.

In addition, MSC established the following ground rules:

- 1) The total manipulator system weight, including the auxiliary lighting boom, shall not exceed 454 Kgms (1000 lbs). The weight of additional root points are not charged against the manipulator system.
- 2) The boom diameter shall be $\leq .229$ m (9") to facilitate stowage in the shuttle.
- 3) A light weight metal such as aluminum or titanium shall be used. Composite materials are not to be used because of their high development costs.
- 4) The station modules [11,340 Kgm (25,000 lbs)] are to be the design drivers. It can be assumed that immediately after capture, the shuttle control system can bring the shuttle kinetic energy down to values lower than for moving modules.
- 5) The 040A shuttle configuration can be used as the reference for the study.

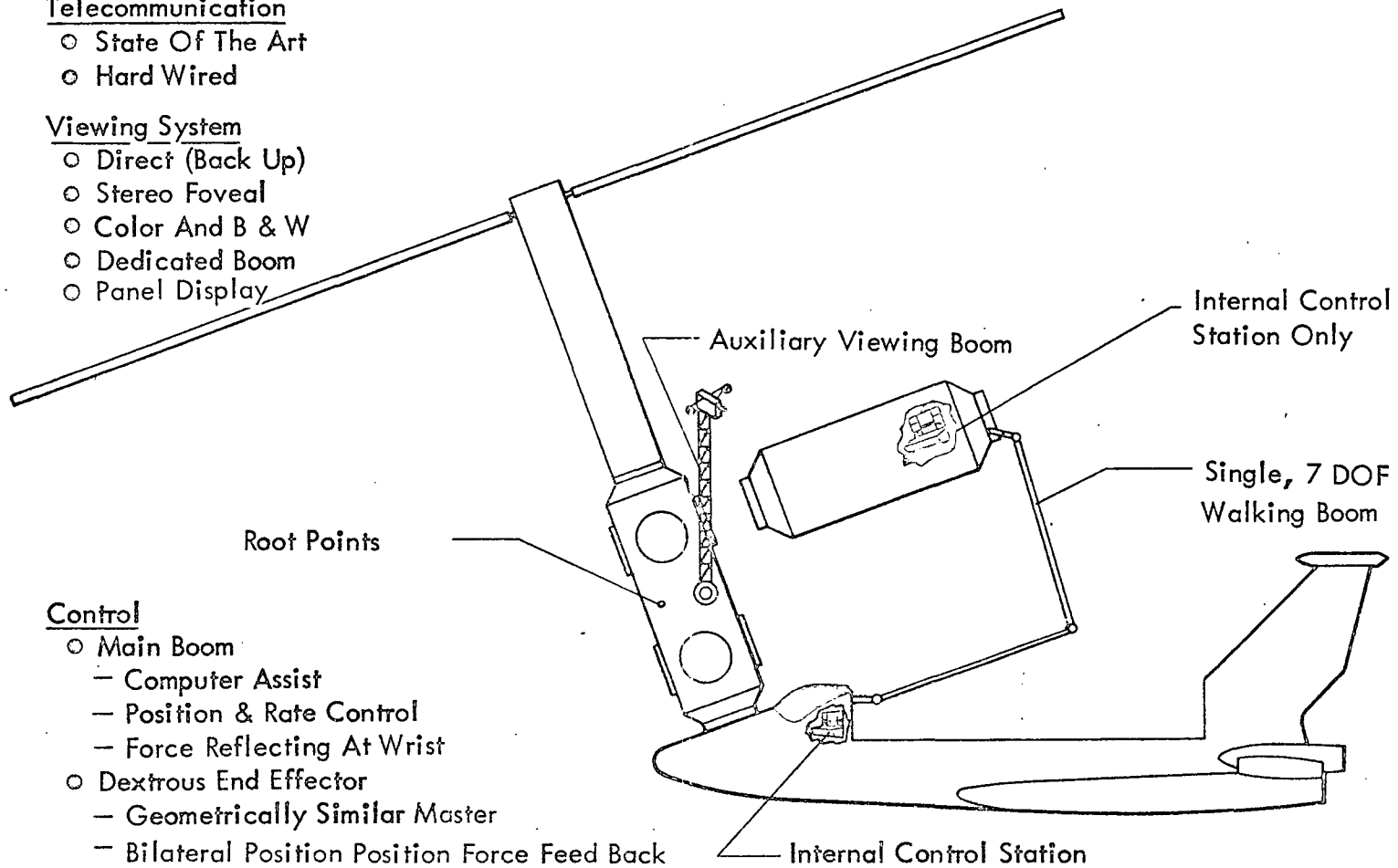
The MSC approved manipulator system concept is illustrated in Figure 2-8.

Telecommunication

- State Of The Art
- Hard Wired

Viewing System

- Direct (Back Up)
- Stereo Foveal
- Color And B & W
- Dedicated Boom
- Panel Display



Control

- Main Boom
 - Computer Assist
 - Position & Rate Control
 - Force Reflecting At Wrist
- Dextrous End Effector
 - Geometrically Similar Master
 - Bilateral Position Position Force Feed Back

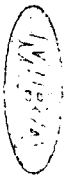


FIGURE 2.8

MSC APPROVED MANIPULATOR SYSTEM CONCEPT

3.0 TECHNICAL DISCUSSION

The Technical Discussion is divided into three parts. Part 3.1 "Introduction" presents some overall program background and describes the approach used in establishing a recommended concept. Part 3.2 "Concepts Development" describes and compares the various concepts considered for each subsystem but generally does not indicate the recommended concepts. Part 3.3 "Concept Selection" describes the recommended system concept and presents the rationale for such recommendation.

3.1 Introduction

The objective of Phase 1 "Concept Selection" of this study was to conceive and evaluate many concepts and, based on a relative weighting of these concepts, recommend that concept which appears most promising for meeting the station/shuttle assembly, cargo handling, berthing maintenance and repair operational and functional requirements. Only the minimum analyses and design necessary to compare and evaluate the concepts was accomplished. Some areas were considered only superficially because they were not fundamental to concept selection, but were equally common to all concepts. The elements appropriate to concept selection and subsequent preliminary design were divided as follows:

<u>Concept Selection (Critical Elements)</u>	<u>Preliminary Design (After Selection)</u>
Single vs Multiple Booms	Structural Material
Boom Degrees of Freedom and Configuration	Actuator Type and Configuration
Man/Machine Interface	Boom Size and Weight
Control Concepts	Control System
Viewing System	Viewing System
Hard Wire vs RF Transmission	Man/Machine Interface
Control Station Location	Power Requirements
Technology Requirements	Data Processing and Transmission
	Thermal Control
	Utility/Growth Potential
	Reliability/Safety

Selection of the number of active booms has a large impact on the entire manipulator system since it affects the way loads are shared, the complexity of and manner in which the booms must be controlled, the man/machine interface and the total amount of support equipment required. Selection of the boom degrees of freedom (DOF's) and configuration is critical since it determines the number of actuators required and the dexterity and capability of the boom. The man/machine interface is critical because the operator will have limited (or no) direct visibility of the work scene, the manipulator is operating in a zero-gravity environment and is relatively weak and slow compared to earth based counterparts and successful task accomplishment without failure or damage to other structures is extremely important because of the human lives involved and the high cost of the missions involved. Control concepts are critical because of the size of the boom and the relative weakness of the booms and actuators in conjunction with the large masses that must be captured, handled and berthed. The viewing system is critical because the operator must be given adequate displays of object geometrical inter-relationships with sufficient resolution and depth perception to remotely accomplish a wide variety of tasks under difficult background illumination conditions. The selection of hard wire vs RF signal transmission is important because ghosting and/or spurious/multipath signal confusion may cause task difficulty and/or accidents. Control station location (internal vs external) is critical because it effects the manipulator safety, mobility and EC/LSS support systems requirements. The technology requirements of any given concept are important because they directly affect the cost and time required to develop an operational capability.

The concept selection study was initiated by reviewing the Statement of Work (SOW) requirements and devising concepts to meet them. The concepts and requirements were then iteratively refined and evaluated leading to a recommended concept with refined requirements. No weight or size limits were specified except that the manipulator system must fit in the shuttle cargo bay [length = 18.3m (60'), diameter = 4.57 m (15')] and be within the payload capability of the shuttle. No task time or boom tip force levels were specified. Task completion within one-half orbit (~45 mins) and the ability to stop a large mass within the operator field-of-view were assumed as reasonable ground rules. Relative approach velocities and angular rates were specified (see station and shuttle parameters given in appendix B. The maximum velocity was given as .1219 m/sec (0.4 fps) in the forward direction. It was assumed that capture could be readily accomplished if the boom tip could move about 5 times faster [.6095 m/sec (2 fps)] than the object to be captured.

A detailed briefing, including 150 illustrations, (see MBA Briefing Aid Document MB-R-71/85) covering all of the concepts and analyses considered was presented to NASA personnel on 30 August 1971. The technical discussion given in the present report includes only the highlights of that briefing. The reader is referred to MB-R-71/85 for further detail if desired.

3.2 Concepts Development

3.2.1 Requirements

The interpretation of the SOW requirements are given in this section. The initial scope of this study was limited to space station assembly, cargo handling and related operations and therefore these interpretations emphasize the space station.

3.2.1.1 General Requirements

The tasks to be performed by the Space Station Teleoperator (Manipulator System) are: to assemble the module space station in earth orbit from modules carried to orbit by the shuttle, to unload and load cargo from the shuttle, to berth the shuttle to the space station in orbit and to perform station repair and maintenance. Desired additional tasks to be performed by the teleoperator are propulsion package replacement and orbital assembly of modular earth orbit or planetary payloads.

The movements of the teleoperator are to be slow with very low closure rates when berthing modules with the station so that berthing loads are absorbed by the teleoperator. The control is to be precise for fine positioning.

The teleoperator will be attached to the space station and will be operated from a manned module providing direct viewing where possible and equipped for limited independent operation with environmental control, emergency life support and electrical power storage. The teleoperator module will be capable of docking on the station's docking ports. The system will be smaller than a station module and be able to fit in the shuttle bay. The teleoperator will consist of one or more booms articulated at the shoulder, elbow and wrist. The booms will be equipped with specialized end effectors and be able to translate and dock modules and to move the T/O module between docking ports on the station. A second set of shorter, general purpose arms may be studied. Visual systems will be incorporated to enable full capability and safety under all operating conditions.

3.2.1.2 Subsystem Requirements

3.2.1.2.1 Boom

The boom will have a force level sufficient to translate and berth (or de-berth and translate) a module in a reasonable period of time and to berth the shuttle. The boom will have a velocity capability to "capture" the shuttle and also a station based free flying experiment module. It will have articulation adequate to reach most places on the assembled station. The deflection will be limited to permit fine positioning. The boom will have end effectors to attach to modules, to the shuttle and to do repair. Reversibility of the boom actuators is desirable but not required. Moderate overloads at the tip will not damage the actuator or the station. Locking of the boom joints in the absence of power or emergency is desired.

3.2.1.2.2 Control Module

The teleoperator control module will have a set of controls and displays sufficient for the operator(s) to view the work area and to control the boom end effectors. The module will provide direct viewing where possible and will have environmental control and emergency life support and electric power storage for limited independent operation.

3.2.1.2.3 Man/Machine Interface

A minimum of training and prior experience will be required for the operator(s). There will be a minimum number of operators (preferably one) required for safe and efficient operation of the teleoperator. Viewing must be adequate to conduct all tasks safely. Computer assistance will be provided for those tasks that are tedious or repetitive and better done under computer control. There will be no encumbrances to the operator.

3.2.1.2.4 Visual System

The visual system is the major information channel of the feedback loop between the manipulator arm(s) and the operator. The visual system will present to the operator sufficient visual information to enable him to conduct the required tasks in a safe and timely manner. Specific requirements cannot be quantified at this time however certain desired features can be qualitatively defined.

The visual system will be the more effective the larger the amount of information carried by it and the more this information is matched to the human visual system. In other words, the information should be displayed in such a way as to introduce no strain on the observer. The same should be said about the visual system controls - that they should be designed to make minimum demands of conscious effort on the part of the operator.

Given the high risk, high stress characteristics of the space environment, as well as past experience with space vehicular operations, it is reasonable to assume that an optimized remote visual system (RVS) with large visual information gathering and display-control (interface) capability will greatly increase safety and speed of operation. It is desirable that the visual system should provide most of the capabilities of the human visual system, such as stereoscopy for precise and immediate depth information, automatic aperture for control of scene brightness conditions, automatic focusing for maintaining a sharp image of the object, eye acuity matching (wide field low resolution combined with narrow field high resolution), color, rotational freedom and also something human vision does not possess - variable field of view (zoom) and immunity to direct or specular reflected sunlight. In addition it is desirable that the camera be mobilized to enable seeing around and behind obstacles.

3.2.1.2.5 Control System

The control system must have a slow and steady response to avoid excess flexing and to facilitate accurate and smooth berthing. The translation mode can have grosser control with a higher velocity attained at a safe distance from the station and shuttle. The control system must also provide sufficient speed, dexterity and feed back to enable the operator to safely and quickly capture co-operative, station keeping vehicles such as the shuttle. The control system must also provide adequate control and feedback for any required end effector - for example a dexterous, anthropomorphic end effector.

3.2.1.2.6 Data Processing and Transmission

This subsystem must process and transmit control and instrumentation signals reliably to effect full control and monitoring of the teleoperator system at all times. The video channels must provide a low noise view of the work area. There must be a minimum impact on the station and shuttle by the telecommunication system.

3.2.2 Boom Configuration

To accomplish all the tasks required of the manipulator boom(s), it must have at least six degrees of freedom. In other words, 6 DOF's are required in order to place a vector at the boom tip at any arbitrary location (x, y, z) at any arbitrary attitude ($\theta, \varphi, \Omega,$) within the operating envelope of the boom. The boom configuration should be chosen so as to be the least complex and the most reliable configuration which will have the ability to perform the required berthing and maintenance functions.

3.2.2.1 Single vs Multiple Booms

The choice of one vs two or more booms is difficult to quantify, however, some general considerations quickly lead to the conclusion that where possible a single boom is preferred. The need for a light weight manipulator system together with the requirement to accomplish reaches up to 18.3m (60') while at the same time holding deflections to acceptable values, say $< 1/2$ m ($\sim 1-1/2'$), leads to low tip forces [$F < 40.5$ kgms (100 lbs)]. Now considering the limited field of view obtainable with reasonable resolution, object velocities must be kept low, say $< 1/2$ m/sec (1-1/2 fps) such that an operator can safely stop a large mass within his field-of-view, say within 1 module diameter 4.27 m (14'). If one now considers a master/slave type control system, the $\sim 20/1$ scale factor requires that the master move at very low linear and angular rates [$< .025$ m/sec (0.9"/sec) and $\lesssim 1.4^\circ$ /sec respectively]. Such low rates would very quickly lead to operator fatigue. Furthermore, any operator perturbations (quick jerky movements) would be amplified by 20/1 causing dynamic problems in the slave. In order to make an

interactive two boom system work; a bilateral, position-position, force feedback control system is required. Without such a control system, the booms would frequently (if not always) be working against each other and structural damage to the booms and/or objects being handled could result. It is an extremely complex problem, well beyond the current state-of-the-art, to control such a multi-jointed (6 DOF each), interactive, two boom system without using man as the controller operating a position-position force reflecting master/slave system. However, for the reasons cited above, the manned master/slave approach is not practical. Clearly more than two interactive booms are more difficult to control than two booms and are therefore even more impractical. One is thus left with the choice of one boom or several independently operated booms. Since only one boom can be operated at a time when moving an object, it follows that for a given total weight a single boom can be made stronger (provide a larger tip force and smaller deflection) than each of several booms, adding up to the same total weight. It is thus clear that if all of the desired tasks can be accomplished with one boom, then a single boom system is preferred.

Consideration of tasks to be performed (discussed in Section 3.2.12 "Utility") shows that a single boom alone cannot accomplish all of the desired tasks. Auxiliary fixtures or devices are required to carry and/or hold objects while the main boom/end effector performs the actual task. However, the auxiliary device or fixture required depends on the task(s) to be accomplished and insofar as the space station/shuttle are concerned, these auxiliary devices can be made lighter than a second arm. Furthermore the auxiliary devices need only be carried or transported when required on a specific task. It is also important to note that space station assembly and cargo handling can be accomplished with a single boom without auxiliary devices or end effectors since the shuttle will be berthed to the station for these tasks.

Reliability is another important consideration in choosing between one or more booms. It can be argued that two equal, independent booms are more reliable than one boom because of redundancy. In theory this is true, but in practice it is only important to the extent that a single

boom system cannot be made reliable enough. There is no reason to believe that a single boom system cannot be made sufficiently reliable, particularly when auxiliary viewing booms (which may be used as an emergency backup) are considered. A basic single boom system was selected for the above reasons.

3.2.2.2 Joint Configurations

In order to select the best boom joint configuration for the present application, a review was made of past and present manipulator systems and related technology (see Section 4.0 "Bibliography").

Excellent reviews of manipulator technology are contained in NASA SP-5097 "Teleoperators and Human Augmentation" 1967, ARAPL-TR-68-75, "Remote Manipulators and Mass Transfer" 1969; AN SC-TE-001W389f, "Nerva Teleoperator Study", 1970; and NASA Document No. 71SD4202, "A Study of Teleoperator Technology Development and Experiment Programs for Manned Space Flight Application, 1971. In addition, new systems have been demonstrated or are under development, which are not universally reported: these are described below.

It is highly important in developing manipulators to thoroughly understand their end use, degrees and type of articulation necessary and operating environment, as well as the uses, kinematics and operator response of past systems. Lack of a thorough understanding of these latter points has led to repetition of numerous mistakes by designers of new or so called advanced systems in the past and present.

3.2.2.2.1 Kinematics

The number and degree of articulation of the joints will affect the versatility and task accomplishment time of a manipulator system. For example, a 5 DOF manipulator (5 joints independent of end effector function) can place an object in any desired location within working range, but cannot place that object in any arbitrary position and orientation at any given place. A 6 DOF manipulator can place an object

in any arbitrary position and orientation, but in general has only one unique solution for any given case. Thus, a 6 DOF manipulator cannot in general locate objects in the presence of obstacles.

In an analytical sense, the six parameters necessary to specify the position and orientation of the end effectors represent six equations. The number of degrees of freedom of the manipulator can be thought of as variables to be adjusted in the solution of these equations. Therefore there is a unique set of values for six variables that can satisfy the six equations, however, if seven variables are available, one of these can be arbitrarily chosen (e.g. to avoid an obstacle) and the remaining six variables are still available to satisfy the six equations.

To illustrate the problem consider Figure 3.2.2-1. Note that the 5 DOF manipulator can trace the straight line path shown, but cannot keep the terminal device perpendicular to the line throughout the sweep. The 6 DOF manipulator can maintain the perpendicular orientation while making the sweep (by rotation of joint 5) but has no ability to avoid obstacles, except for flipping the elbow (joint 3) to the mirror image position. The 7 DOF manipulator can also trace the path, but has considerably more freedom to complete the task in the presence of obstacles.

3.2.2.2.2 Design Rules

An in depth study by MBA of all significant manipulators developed to date has led to several general design rules. The study was conducted with the aid of consultants who have operated or designed practically all systems. Manipulator site visits were made to provide first hand experience.

A study of the G.E. (Mosher) Handyman illustrates the first three rules. The Handyman (Figure 3.2.2-2) is used as an example because it had the minimum six DOF, however they were awkwardly placed. The awkwardness stems from the fact that there was only half of a Hooke joint (universal joint) at the wrist and the master and slave were not kinematically similar. These points have not been previously documented

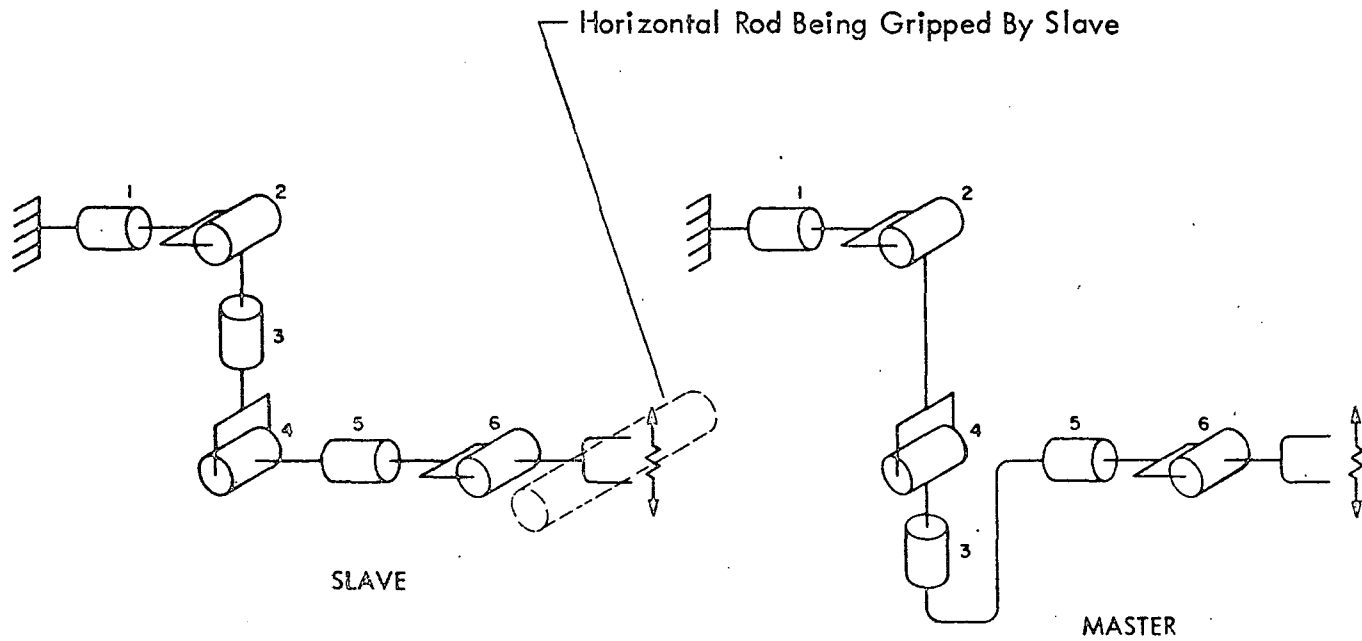


FIGURE 3.2.2-2.
HANDYMAN KINEMATIC ARRANGEMENT DEVELOPED BY G. E. (R. MOSHER)

about the system, which is esteemed as an advancement in the state-of-the-art. They can be verified by study of the photographs on pages 176, 177, 182 and 183 of "Human Factors of Remote Handling in Advanced Systems", 1961. These fundamental problems with the system have been masked in the literature by additional problems with the control system.

From Figure 3.2.2-2 note that if a horizontal rod was grasped at right angles to the forearm axis and pushed into a hole aligned with the rod, the upper arm rotation (slave joint 3) and elbow (slave joint 4) had to be used to make up for disorientation at the wrist caused by the shoulder motions (joints 1 & 2). Note that any motion of joint 4 at the master causes the axis of joint 3 at the master to lose alignment with the axis of joint 3 on the slave, destroying kinematic similarity between the master and slave (i. e. joint 3 on the master is misplaced). The subject operation could be accomplished, but it was difficult and extremely unnatural. Incidentally, one of the primary tasks which justified development of the system (\approx \$3 million dollars) was to insert and remove horizontal slender reactor control rods.

The answer to the problem is that in working with position controlled systems kinematic similarity between master and slave must always be maintained and the three rotational degrees of freedom or orientator (wrist) actuators must be located as close to the terminus (end effector) as possible. This also minimizes location changes when the orientors are actuated. Therefore, Rule 1: A manipulator should be designed kinematically to accomplish the primary task it must perform with ease. Rule 2: To minimize operator training, task time, and task mistakes under stress the principal of kinematic similarity between master controller and slave must be maintained. Rule 3: The three rotational (or orientor) axes should be as close to the terminus as possible. (See Figure 3.2.2-3.)

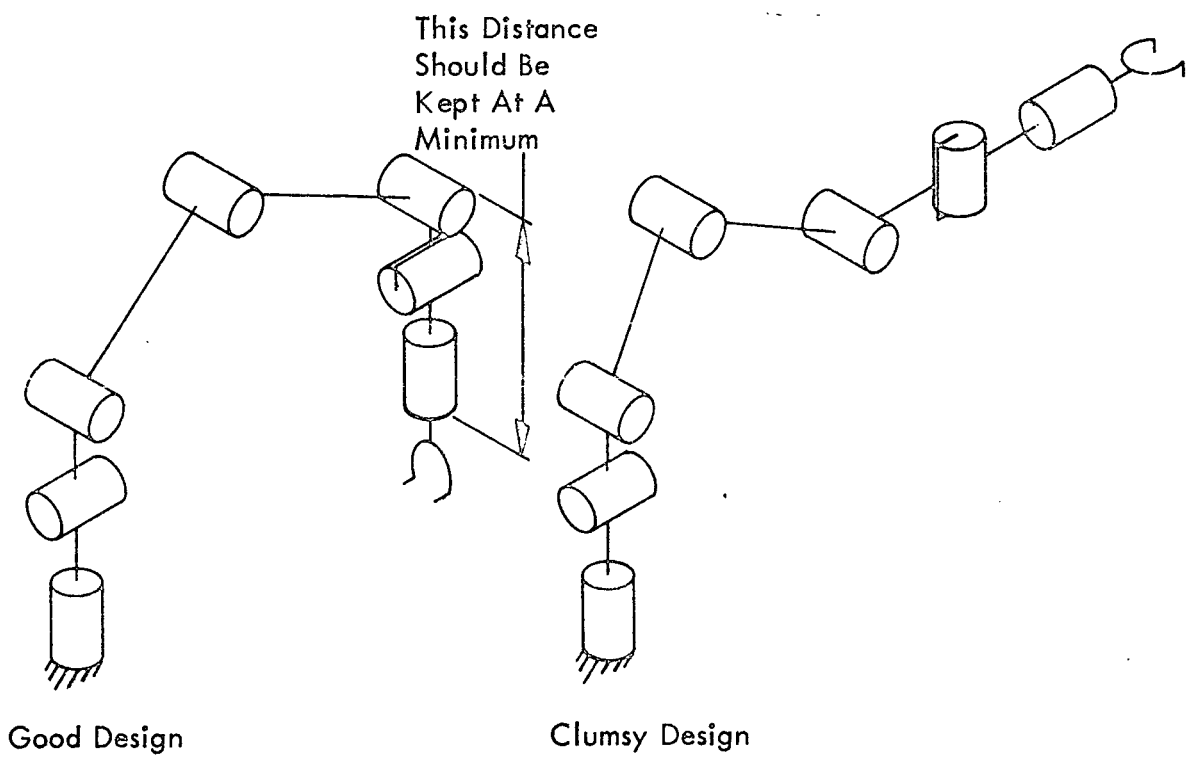
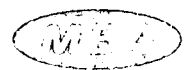


FIGURE 3.2.2-3.
RULE III ORIENTOR AXES LOCATION



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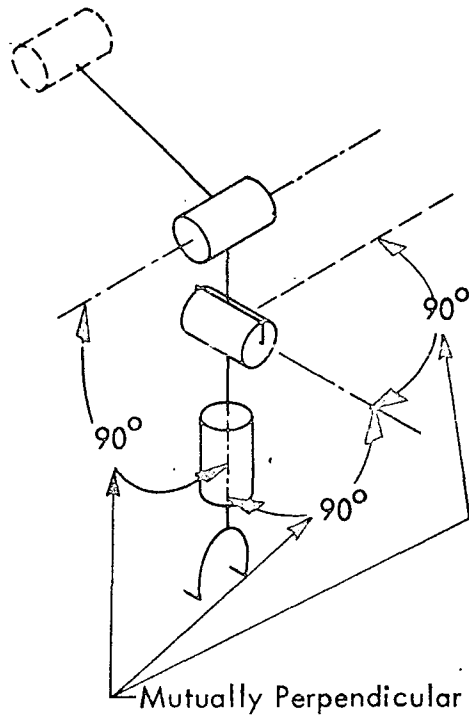
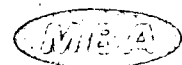


FIGURE 3.2.2-4.
 RULE IV PERPENDICULAR ORIENTOR ACTUATORS
 FOR NORMAL OR PREFERRED POSITION



The three orientor axes should be mutually perpendicular. It can be shown however, that rotations of one orientor with respect to another can produce axis alignment of any two of the orientor axes (gimbal axis transfer). There are then only two effective axes. There is usually a normal, preferred, mid or neutral arm position. Therefore, Rule 4: In the preferred position the three terminator orientor axes should be mutually perpendicular, (See Figure 3.2.2-4.).

For the same reasons, this mutual perpendicularity also follows for the locators, or "shoulder actuators" whether they be pure transitional motions, quasi translations as produced by a spot mounted manipulator (shoulder attached to a stationary mount), or combination thereof. This will produce the greatest displacement for the smallest actuator arc. Therefore, Rule 5: In the preferred position, the three locator or shoulder axes should be mutually perpendicular (See Figure 3.2.2-5.).

It is more natural for a man to turn through large angles from side to side than to look straight up or straight down simply because he has learned to stand erect in a one "G" environment. (i. e. the population is stereotyped). If a manipulator's grounded motion has a vertical axis and moves in a horizontal plane (and consequently the rest of the manipulator moves horizontally), the operator merely turns his head or body horizontally to stay in alignment with it. Because the work surface is usually a horizontal plane (across body-right-left), it is convenient with a spot mounted manipulator to have one joint that will allow motion across the work surface (horizontal) without digging into it. The grounded vertical axis is the only one that will guarantee this motion, since axes downstream will not remain vertical as actuators are moved. Also considering a spot mounted force reflecting manipulator, a horizontally swinging, vertical axis motion does not require counterbalancing. If the grounded axis is vertical, then that motion need not be counterbalanced, thereby simplifying the total system. This point is significant for space manipulators in that units built for training simulators will then be simplified. Therefore, Rule 6: For spot mounted manipulators the actuator connected to the ground should have a vertical output axis, (See Figure 3.2.2-6.).

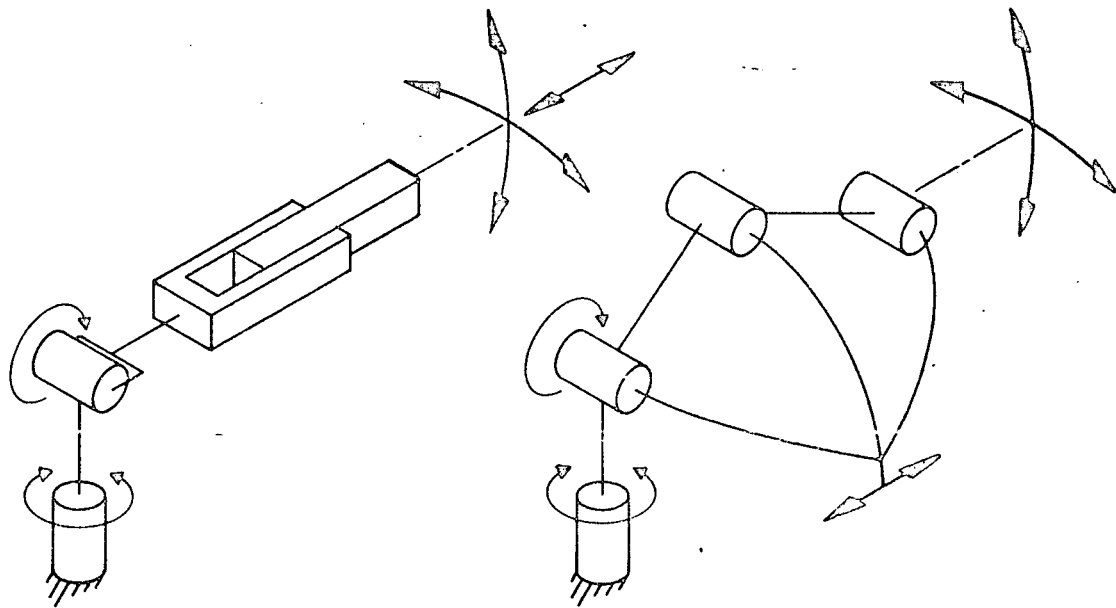


FIGURE 3.2.2-5.
 RULE V MUTUALLY PERPENDICULAR LOCATOR ACTUATORS

MBA
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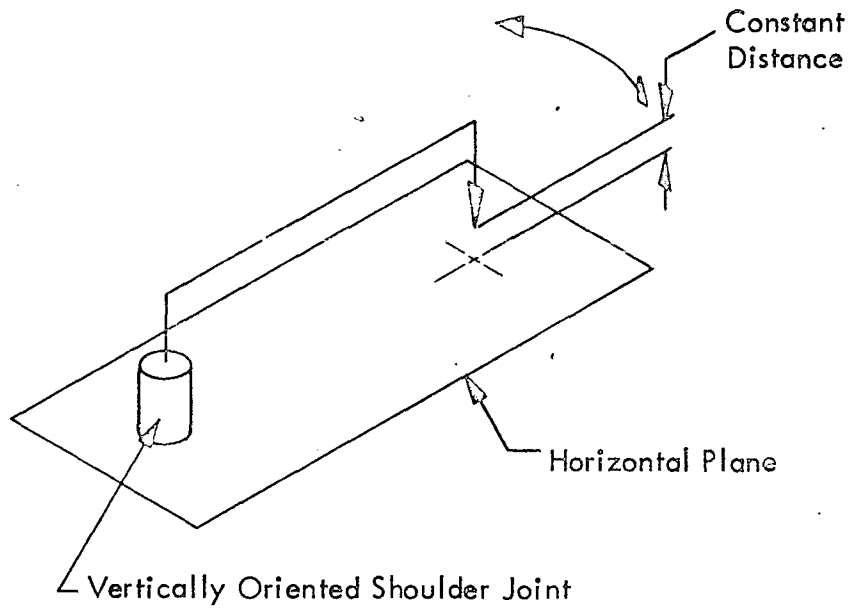
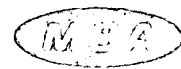


FIGURE 3.2.2-6.
 RULE VI HORIZONTAL TIP MOVEMENT
 (SPOT MOUNTED MANIPULATORS)



3331-9816

3.2.2.2.3 Manipulators Not Yet Covered in Open Literature

A brief description of recently developed manipulators which are not fully covered in the open literature follows. In studying this data, bear in mind the design rules of the previous discussion.

Rancho 3rd Generation Arms

These arms are an outgrowth of the externally powered orthotic arms developed at Rancho Los Amigos Hospital under VRA Grant No. RD-518. The general kinematic arrangement between master and slave is presented in Figure 3.2.2-7(a). Note the lack of kinematic similarity between the exoskeleton master and slave, which has led to significant degradation in performance to date. Other problems stem from the fact that the system was initially designed to take advantage of the natural damping of the human arm, and to reduce cost, it is fabricated from all right hand parts, which leads to further dissimilarity between the master and slave. It was intended to be a low initial cost position controlled electro mechanical DC motor driven system with no force feedback. Despite the inherent faults of the system it has served an important function in spurring forward teleoperator system development. Units have been procured by many organizations and institutions. All have been reworked to better serve the needs of their owners. A third generation system is owned by NASA/MSFC. This system is currently on loan to Bell Aerosystems for use in FFTO simulations.

Brookhaven Arm

The general kinematic arrangement of this system is shown in Figure 3.2.2-7(b). This arrangement is identical to the MARK E4A except for an interchange of joints 1 and 2 and rotation of the new joint 1 axis to a horizontal orientation. The Brookhaven arm was developed under AEC funding at Brookhaven National Laboratories over a four or five year period. No motion pictures of its operation were produced and few persons besides its developer (C. Flatau) have had the opportunity of operating it. At the time it was operated by MBA personnel (May 1970)

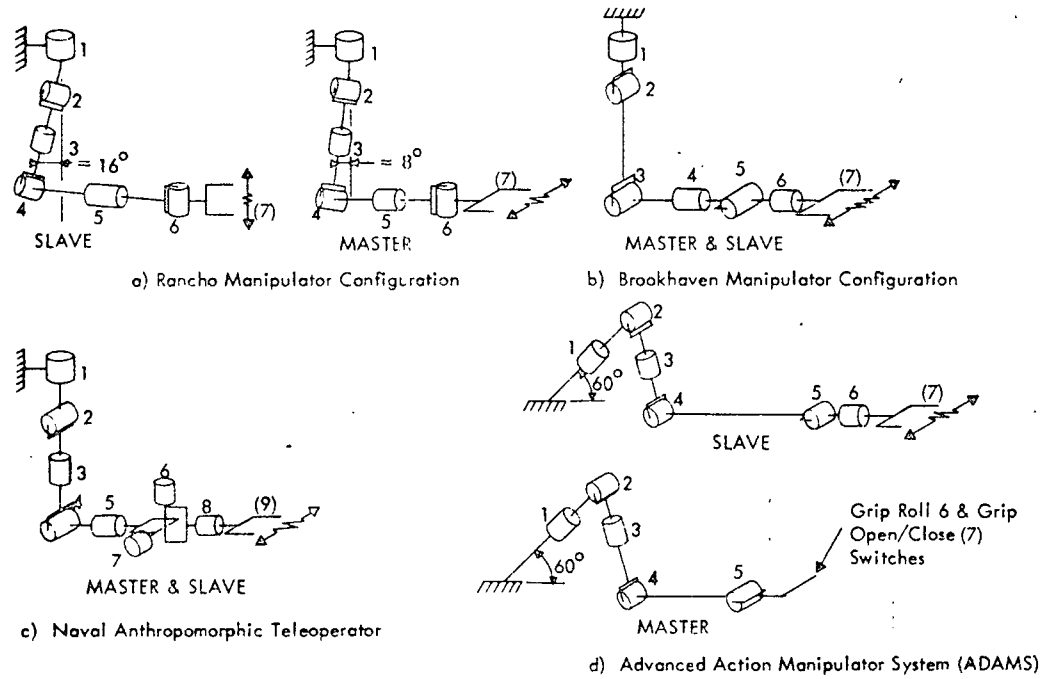


FIGURE 3.2.2-7.
KINEMATIC ARRANGEMENT OF NEW MANIPULATOR SYSTEMS

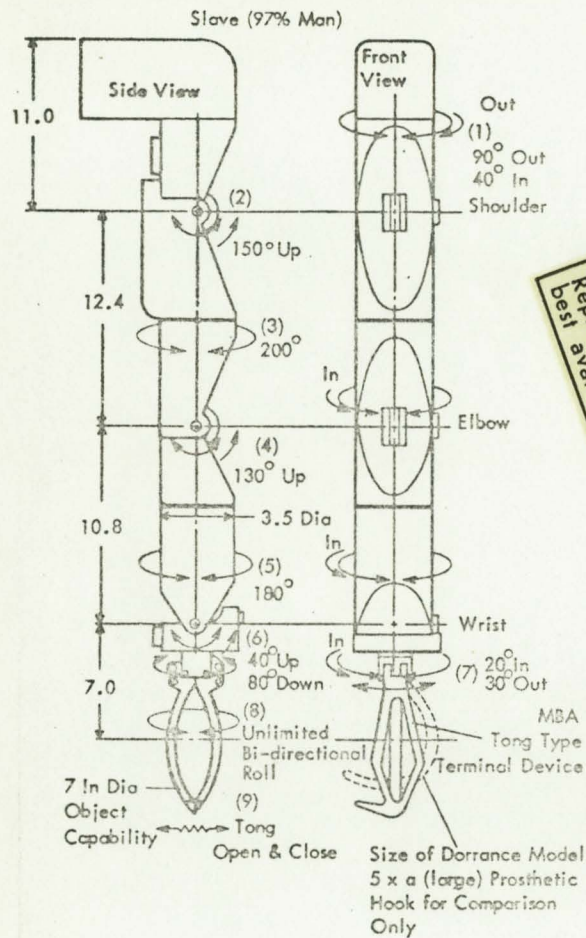
only the wrist joint was functioning without palsy and because of limited development funds the manipulator has never been brought into a fully operational condition. It is the first electro mechanical system developed which incorporated DC motors with harmonic speed reducers and strain transducers for force feedback. All joints incorporated force feedback.

Naval Anthropomorphic Teleoperator (NAT)

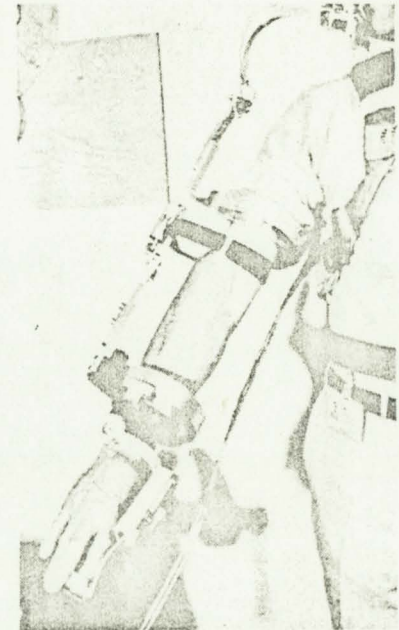
The kinematic arrangement is shown in Figure 3.2.2-7(c) and the system is shown in more detail in Figure 3.2.2-8. It was developed by MBA over a nine month period under Navy funds administered by NASA/SNPO. It is an electro-mechanical-hydraulic-pneumatic hybrid 9 DOF man equivalent (dexterity, range of motion and strength) position servo controlled system incorporating proportional force feedback in the grip and step force feedback in the elbow. The master controller is a full motion exoskeleton. It was specifically designed for ordnance disposal and defuzing delicate submunitions. Contract design requirements included unusually smooth highly controlled dexterous action, the use of nonmagnetic materials, no radiated EMI, underwater operation, sandy beach and desert operation, high pantographic fidelity between master and slave, ruggedness and high reliability. Electric drives for this specific system were excluded on the basis of system reproduction cost, radiated EMI and magnetic materials.

The exoskeleton is designed to readily fit 5 to 97 percentile men. It can be attached to a wall or chair and operated in either of the configurations illustrated for the Brookhaven arm in Figure 3.2.2-9.

The slave incorporates a semi-monocoque construction. As a consequence it is the first system capable of lifting more (20 lb. at any one joint) than it weighs (16 lb.). The grip is designed to accomplish extremely delicate and minute operations as well as handle spheres, cones and cylinders up to 7 inches in diameter and weighing up to 20 lb. The system further incorporates a design which readily allows the addition of a remote quick release for the claws and easy conversion to a reversible electric motor driven system (DC torque, gear reduction and ball screw actuator). Its kinematic arrangement (Figure 3.2.2-7(c) duplicates



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ADJUSTABLE RANGE
 10.3 in. - 13.2 in. Upper Arm
 9.4 in. - 10.5 in Lower Arm

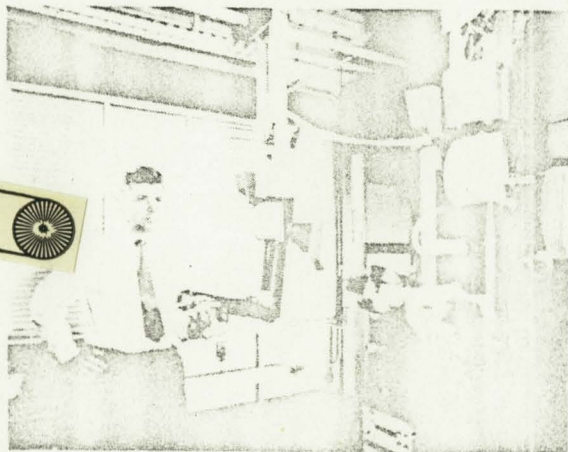
a) Slave size and range of motion - arm is capable of lifting 20 lb. at center of grip using any one or all joints simultaneously over their full motion range

b) Master - proportional force feedback on grip - step force feedback on elbow.

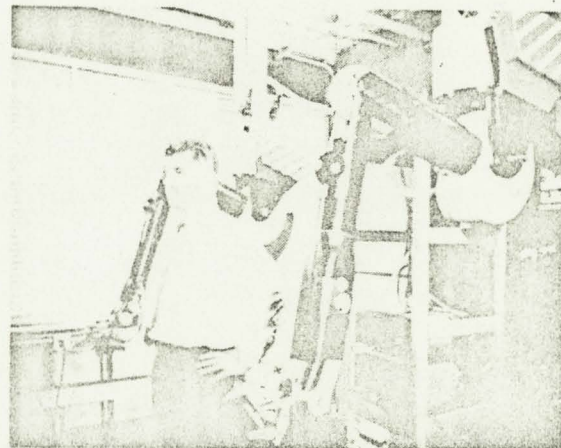
FIGURE 3.2.2-8. MBA DEVELOPED NAVAL ANTHROPOMORPHIC TELEOPERATOR (NAT)



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Anthropomorphic Elbow Configuration



Over the Shoulder Configuration

FIGURE 3.2.2-9.
BROOKHAVEN ARM. Developed by C. Flatau. First Working compact bilateral-force reflective servo manipulator using DC servo motors/harmonic drive units. Incorporates explicit force feedback, in addition to the customary position feedback. The slave (less counterweights) weighs 60 lbs and can lift 30 lbs.

that of the human arm, except for the continuous grip roll beyond the wrist gimbal. Specifically designed for low cost in production (\$20K in quantities of 40 or more) using off-the-shelf commercially available components (where possible), the system has already established a new state-of-the-art in servo controlled teleoperator systems.

An interim performance demonstration was made for NASA, Navy, AEC and MIT personnel on 22 July 1971. Performance of the arm in grasping and lifting large 20 lb. test objects as well as threading a small household needle, handling raw eggs, removing and replacing nuts from bolts and replacing small electronic components from printed circuit boards, has earned the ARM the reputation of being the most advanced teleoperator system developed to date. The above tasks were done while viewing through a stereo TV system. The needle threading, trimpot adjustment and operational amplifier tasks could not be accomplished without the TV system stereo attachment.

Total system tests of the right arm were successfully accomplished in October 1971. These tests included sea water immersed operation at a depth of $\sim 8\text{m}$ (25'), operation from -18°C (0°F) and 59°C (120°F), operation in sand storms. The dexterous tasks described above were repeated and more recently unlocking a padlock, removal and disarming a mock homemade bomb and defusing a buried (inert) standard mine were accomplished.

Advanced Action Manipulator (ADAMS)

This system is a 6 DOF electro-mechanical, DC motor driven, position controlled system developed by GE for NASA/MSFC. It incorporates a fully counterbalanced master, a wide range of motions, alternate switch control and can lift a six lb. payload. It was developed for adaptation to underwater use at a later date. Its kinematic configuration is shown in Figure 3.2.2-7(d). It was demonstrated in the Fall of 1971 at NASA/MSFC.

NASA/AMES Teleoperator

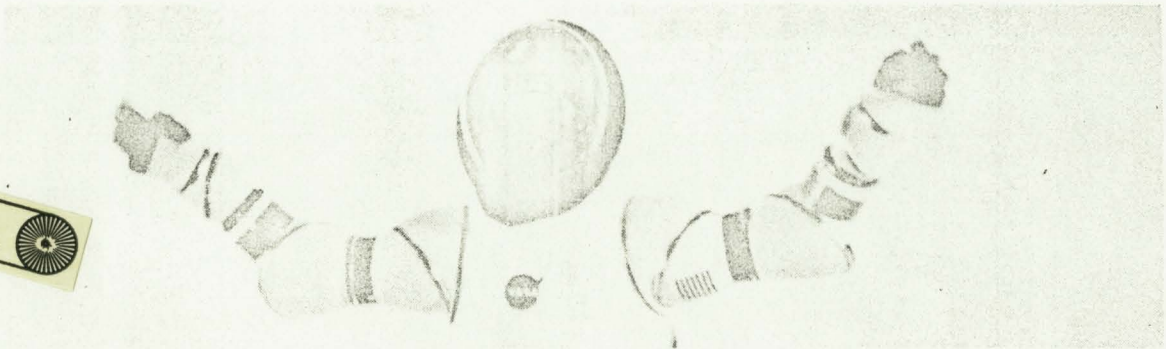
This unique and truly innovative system is an adaptation of the NASA/AMES developed hard space suit (Figure 3.2.2-10) which utilizes a unique arrangement of rotary joints (stove-pipe configuration) to closely approximate the kinematics of the human arm. It incorporates an electro-mechanical DC motor/harmonic speed reducer position controlled system with no force feedback. The primary structure is fiberglass and it can be readily sealed from the environment. All joints are designed around identical DC motor/harmonic gear reducer/potentiometer drive elements.

The master is a light weight version of the slave with 1:1 kinematic correspondence. The slave capability is 22 lb. and its weight is approximately 22 lb., making a 1:1 payload to weight ratio. It will eventually incorporate a form of tactile feedback being developed at Stanford Research Institute, similar to that provided by the hair on a human arm. Adaptation to force feedback will be difficult due to a tendency to mechanically lockup in specific configurations. Initial assembly has been completed and is currently undergoing debugging.

3.2.2.3 Candidate Manipulator Boom Configuration

On the basis of the above design rules, past and current manipulator configurations and experience, and on consideration of the present tasks to be performed, six candidate boom configurations were evolved for evaluation. These are shown in Figure 3.2.2-11. Three of the configurations are shown with a manned module which supplies one of the degrees of freedom. If it is undesirable for the manned module to rotate shoulder vertical axis rotation can be supplied by adding such a joint to the boom. The other three boom configurations are unmanned, symmetrical walking boom designs; that is, they can be walked end over end from one root point to another. They could also be used on the manned module by putting a root point on top of the module.

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Hard Suit Configuration

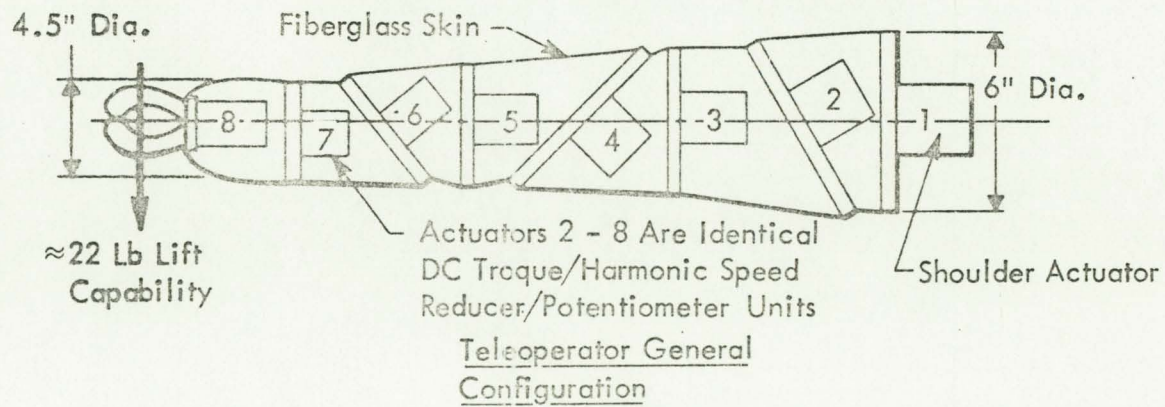


FIGURE 3.2.2-10.
NASA/AMES TELEOPERATOR



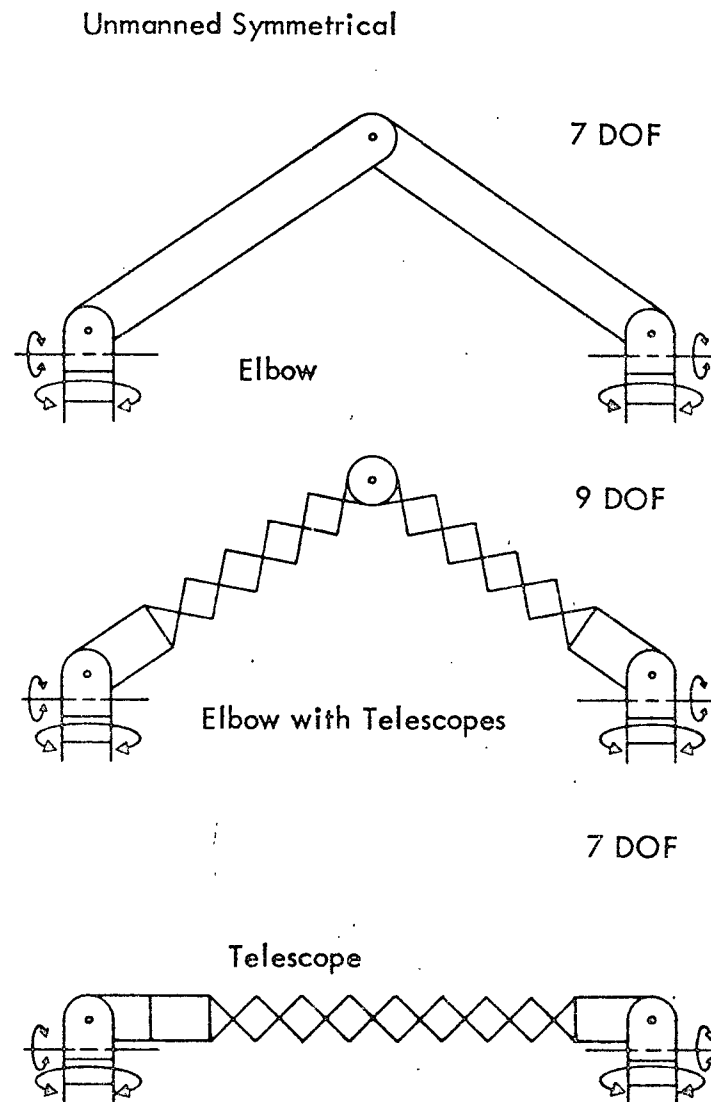
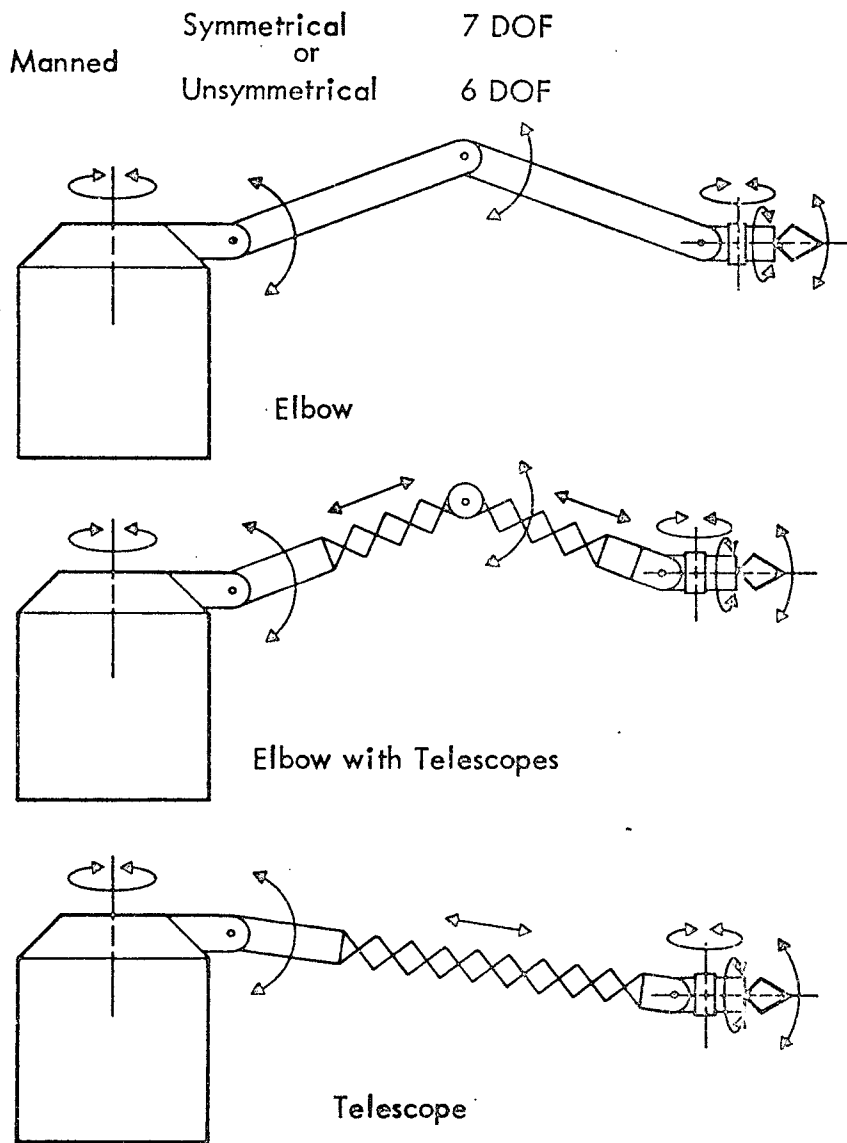


FIGURE 3.2.2-11.
CANDIDATE BOOM CONFIGURATIONS



2 (9)

3.2.3 Actuators

Selection of actuator type (i. e., electric vs hydraulic and detail configuration) is not critical in overall concept selection. Some general considerations relative to concept selection are given below.

In order to select the best actuator, several parameters of the boom design must be established. The boom envelope (maximum diameter) will effect whether electric or hydraulic actuators are used. The weight limitations, force levels desired and state-of-the-art will also have considerable effect on the design.

The serpentuator type actuator is useful if the output motion required is $\pm 180^\circ$. (The serpentuator actuator consists of two pivots connected by a link such that the arms of the joint can fold back $\pm 180^\circ$ upon themselves.) However, the present boom design only requires $\pm 90^\circ$ for the elbow joint and less for the rest of the pivot joints. A disadvantage of the serpentuator joints is that they cannot be used for roll motion. Two separate types of actuators would therefore be needed which would increase both the development and fabrication cost.

Whether backdriveability of the actuators is needed is not clear at this time. The hydraulic cylinder/linkage actuator is the only truly backdriveable at the high torque-low angular speed range which is required. For backdriveability, the hydraulic cylinder would require pressure feedback, either by pressure control servo valves or a flow servo valve with a pressure transducer or strain gaged structural member.

Having the actuator non-backdriveable could be an advantage. When the manipulator boom is not in service, the joints would keep their position and "drift" of the arm would be avoided. Slip clutches should however, be added so that if the boom is overloaded, the clutches will give rather than damage the boom itself. These clutches would be set to release at the maximum torque level of the actuator. Potentiometers or angle decoder positioners would still keep track of the angular position of the joints so that control of the boom is not impaired by the addition of the slip clutches.

3.2.4 Boom Dynamics

In order to identify and understand the dominant dynamic phenomena associated with the manipulator boom the following representative system estimates of the characteristics of a final system were assumed:

Overall length	18.3 m	(60 ft)
Tube diameter	30.5 cm	(12 in)
Wall thickness	3.2 mm	(1/8 in)
Material	AL 7075-T6	
Maximum Tip Force (for Boom Straight Out)	444 Newtons	(100 lbs)

Several additional constants were assumed. Of primary interest are the following:

Cargo module mass	11,300 kg	(778 slug)
Pitch moment of inertia	$1.03 \times 10^5 \text{ kg m}^2$	$(7.6 \times 10^4 \text{ slug ft}^2)$
Shuttle mass	$1.29 \times 10^5 \text{ kg}$	(8,850 slug)
Yaw moment of inertia	$2.05 \times 10^7 \text{ kg m}^2$	$(1.52 \times 10^7 \text{ slug ft}^2)$
Relative velocity	.122 m/sec	(.4 ft/sec)
Angular rate	.1 deg/sec	

3.2.4.1 Stiffness Properties

The stiffness of the reference boom in the straight out configuration is approximately 1,250 N·m (85 lb/ft) in bending and 1,830 N·m/deg. (1,340 ft. lb/deg) in torsion. These two structural parameters of the boom in its most compliant position are directly proportional to the sectional and polar moments of inertia of the boom. For the thickness to diameter ratios considered herein, the moment of inertia and hence the stiffness for a given diameter is approximately proportional to the wall thickness, as is the boom weight. Thus the tradeoff between weight and stiffness is fairly linear for varying wall thickness of interest.

3.2.4.2 Natural Frequency

Perhaps the most startling property exhibited by the boom is the natural frequency of the system when attached to a typical payload mass. Because the natural frequency is so low for the system under consideration, it is more convenient to describe the system in terms of the natural period. The natural frequency for a given mass system is inversely proportional to the square root of the beam stiffness. Hence, it exhibits a similar dependence on the beam structural moment of inertia. Figures 3.2.4-1 and 3.2.4-2 show curves of the natural period for bending and torsional modes, respectively, with the boom straight out for the two primary masses (the module and shuttle) that will be manipulated by the system. In both cases it is assumed that the boom is fixed to an object of infinite mass. Although this is not actually the case, it does represent an upper limit on the expected natural period. Also indicated in the figures are the values of the natural period for the reference boom configuration.

3.2.4.3 Worst Case Beam Loadings

A series of capture scenarios were postulated to examine the magnitude of the largest expected loadings on the boom. In each of these, it was assumed that the boom was locked in a particular orientation, such as straight out or with the elbow bent at a 90° angle. In each of these cases it was assumed that the maximum residual relative velocity or angular rate existed for the shuttle and that all of the resultant kinetic energy was absorbed by the boom itself. Table 3.2.4-1 is a summary of four different loading conditions. This table also presents the rationale for selecting a constant diameter, constant wall thickness tubular section as the preferred shape which best satisfies all possible beam loadings.

3.2.4.4 Stopping Distance

A realistic estimate of the stopping distance for various payload objects can be calculated by assuming the maximum tip force of 45 kg (100 lb) is used to absorb the objects' kinetic energy. These stopping distances are shown as functions of velocity for the cargo module and the shuttle in Figure 3.2.4-3. Stopping distance is a key factor in determining the maximum velocity at which objects can be safely handled.

Cantilever Deflection
 18.2 (60 ft) Aluminum Beam

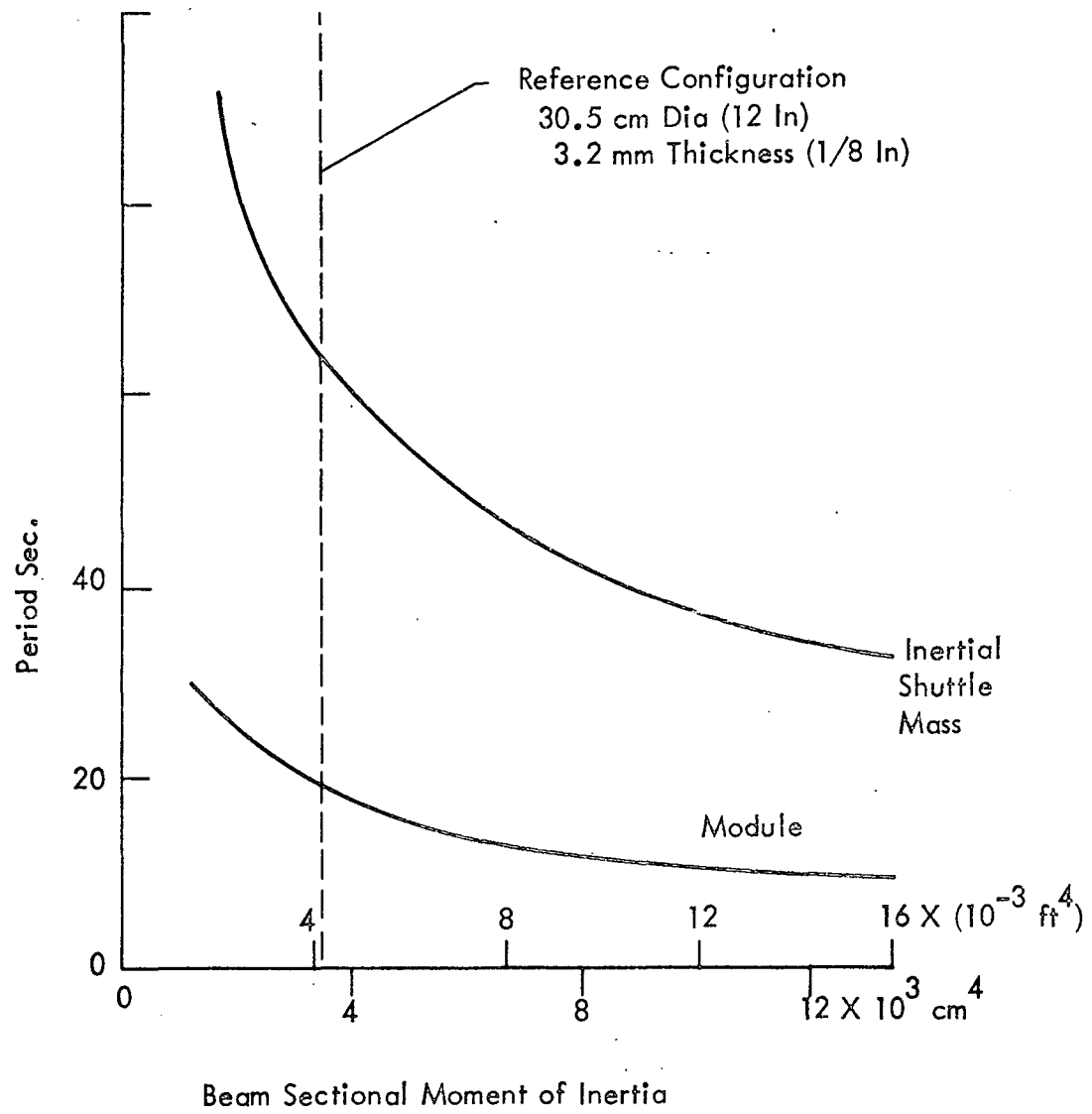
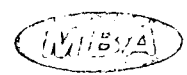


FIGURE 3.2.4-1.
 BOOM BENDING MODE NATURAL PERIOD
 (BOOM STRAIGHT OUT)



Torsional Deflection 18.2 (60 ft) Aluminum Beam

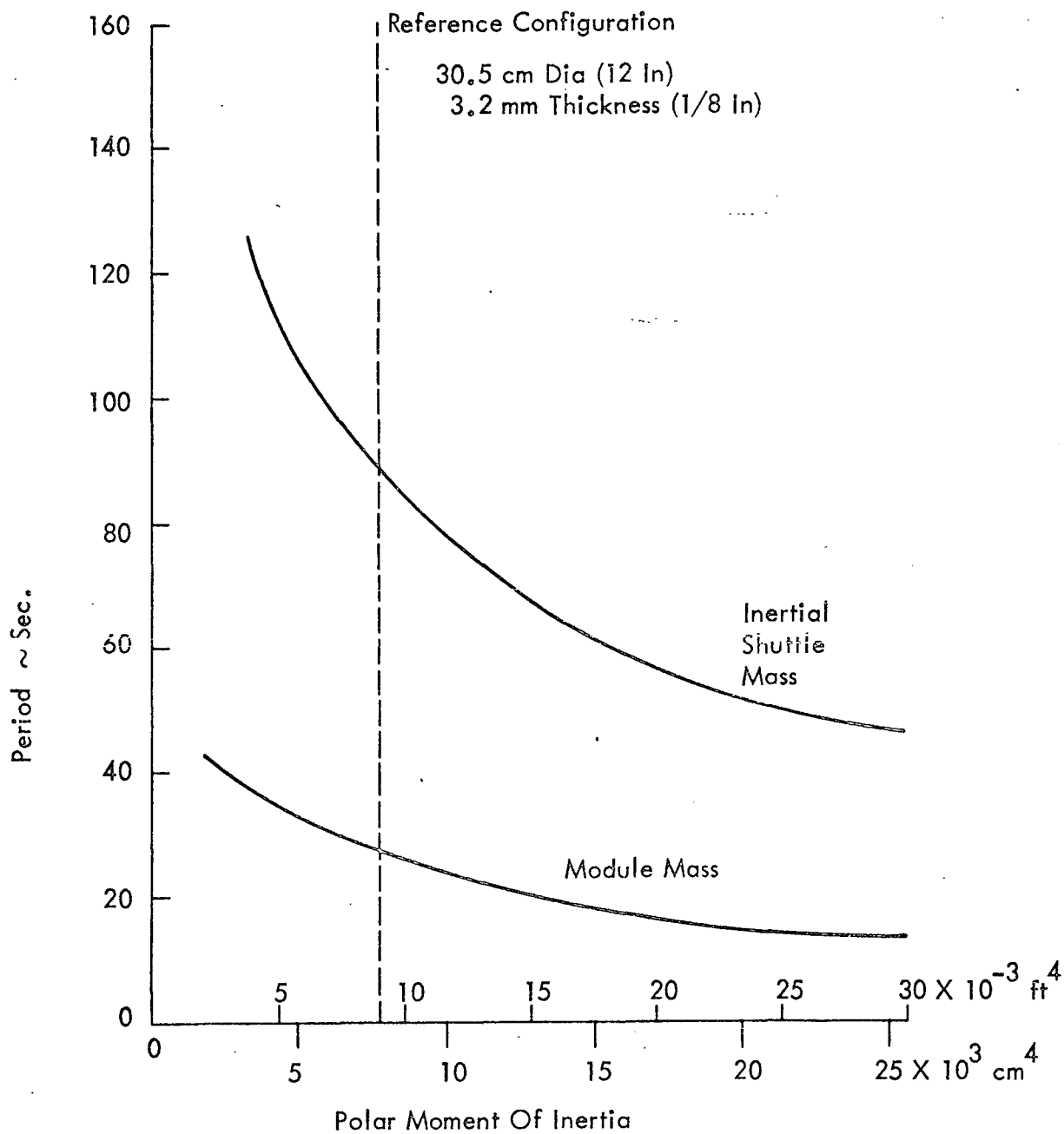
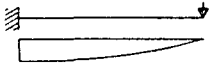
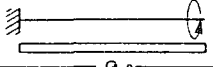
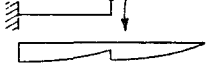



FIGURE 3.2.4-2.
BOOM TORSIONAL MODE NATURAL PERIOD
(BOOM STRAIGHT OUT)



WORST CASE BOOM LOADINGS

Case	Loading Constant Strength Shape	KE	Spring Constant	Max Tip Force	Max Bending Force	Max Torsion	Max Bending	Max Torsions	Stopping Distance
1		1050 Nm (708 Ft-lb)	126 kg/m (85 lb/ft)	156 kg (348 lb)	2.81×10^4 Nm (2.1×10^4 Ft-lb)	----- -----	1.24×10^8 Pa (1.8×10^4 psi)	----- -----	1.23 m (4.1 Ft)
2		31 Nm (23 Ft-lb)	1800 Nm/deg (1340 ft-lb/deg)	----- -----	----- -----	2.55×10^3 Nm (1.9×10^3 Ft-lb)	----- -----	5.6×10^6 Pa (8×10^2 psi)	1.4° (1.4°)
3		1050 Nm (708 Ft-lb)	201 kg/m (135 lb/ft)	172 kg (403 lb)	1.6×10^4 Nm (1.2×10^4 Ft-lb)	1.6×10^4 Nm (1.2×10^4 Ft-lb)	6.9×10^7 Pa (1.0×10^4 psi)	3.5×10^7 Pa (5.1×10^3 psi)	1.06 m (3.54 ft)
4		1050 Nm (708 Ft-lb)	506 kg/m (340 lb/ft)	325 kg (717 lb)	2.81×10^4 Nm (2.1×10^4 Ft-lb)	----- -----	1.24×10^8 Pa (1.8×10^4 psi)	----- -----	.62 m (2.1 ft)

Desired Shape

Torsion - Constant Cross Section - Hollow Tube

Beaming Loading in Arbitrary Plane - Circular Symmetry

To Satisfy Cases 1 - 4 - Constant Cross Section



CONSTANT CROSS SECTION
TUBULAR BOOM

53

3341-9863



TABLE 3.2.4-1.
WORST CASE BOOM LOADINGS

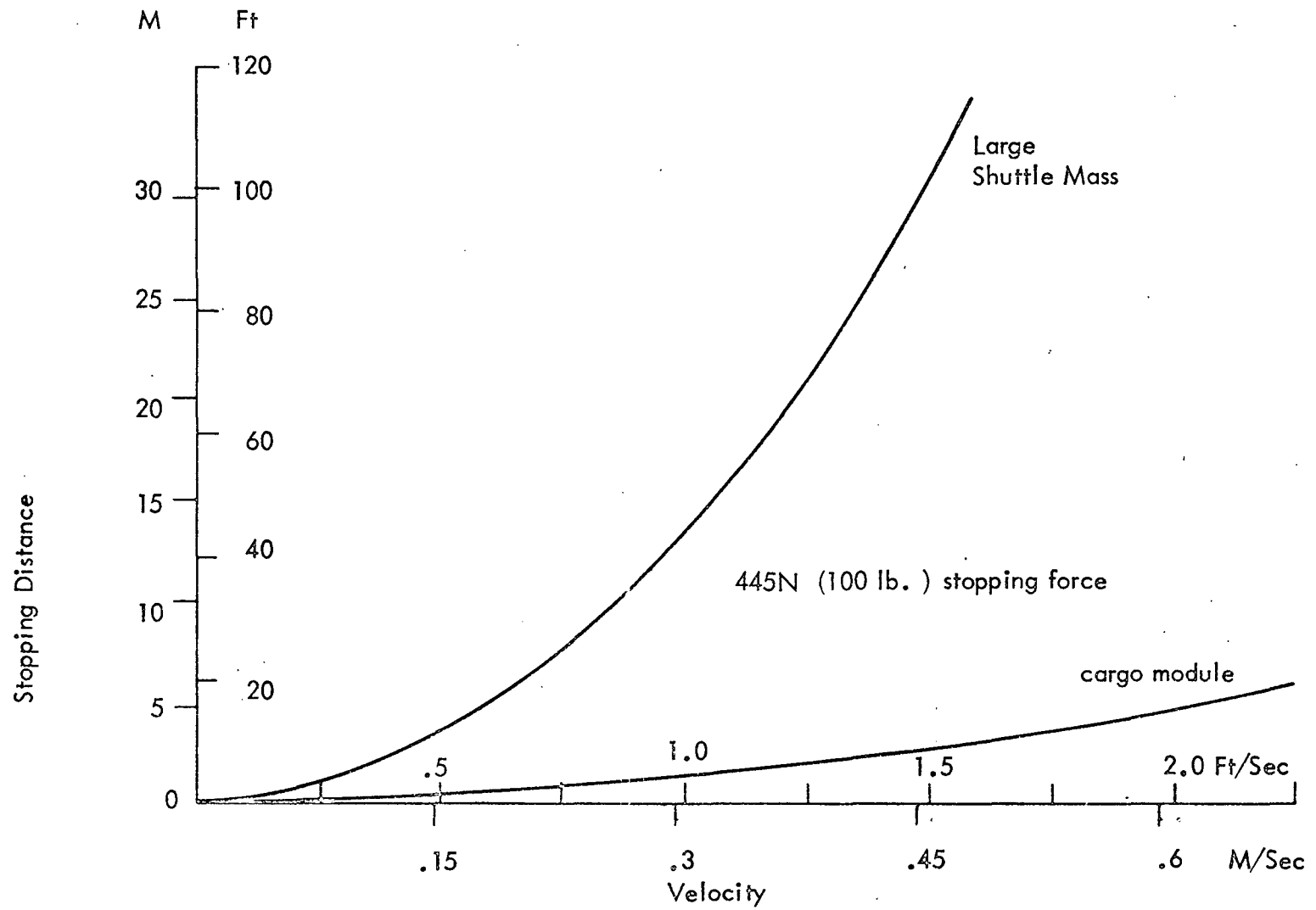
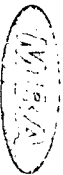


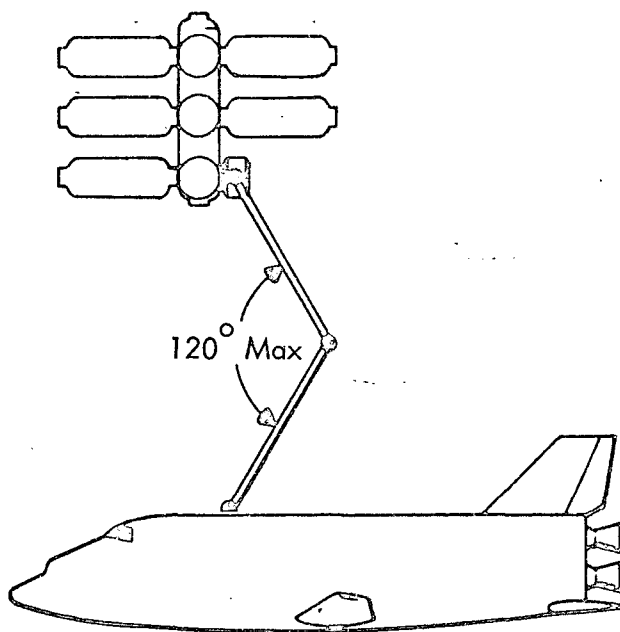
FIGURE 3.2.4-3.
OBJECT STOPPING DISTANCES



Two possible methods for shuttle capture are shown in Figures 3.2.4-4 and 3.2.4-5. In Figure 3.2.4-4 it is assumed that shuttle is much less massive than the space station. The boom is bent at the elbow so that the residual velocity of the shuttle in any direction can be dissipated without endangering the space station or fully extending the boom. The 120° max angle at the elbow allows a minimum of 2.4m (8 ft) of travel in any direction. Figure 3.2.4-5 shows a possible shuttle mounted application of the system, in this manner capture can be accomplished with a maximum relative stopping distance of 1.1m (3.5 ft).

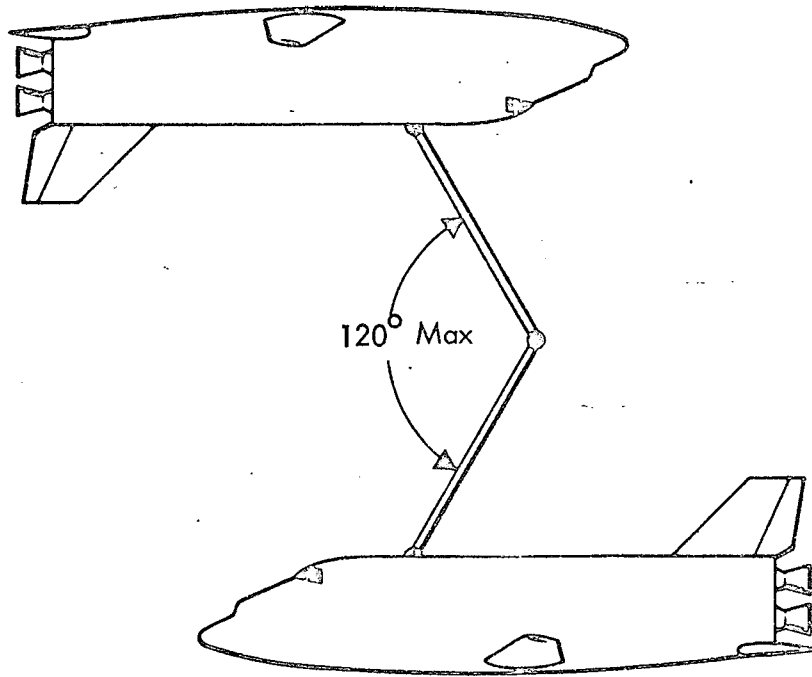
3.2.4.5 Power Requirements

If a speed limit on the order of .3m/sec (1 ft/sec) is assumed, a maximum power of 134 watts (0.18 hp) is required by the shoulder actuator when the boom is straight out, moving at .3m/sec (1 ft/sec) and exerting the assumed maximum force of 45.0 kg (100 lbs). During complex operations as many as three actuators might be operating at somewhere near the peak level. This effect plus reasonable allowances for motor and transmission efficiency suggests a maximum total power requirement for the actuator portion of the baseline system of about 1100 watts.



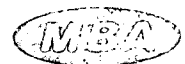
- Controlled Braking at Actuators
- Maximum Stopping Distance 2.4 m (8 Ft)
- ⊗ Maximum Base Torque 3140 Nm (6000 Ft/lb)

FIGURE 3.2.4-4.
SHUTTLE CAPTURE



- Controlled Braking at Actuators
- Maximum Relative Stopping Distance 1.1m (3.5 Ft)
- Maximum Base Torque 8140 Nm (6000 Ft/lb)

FIGURE 3.2.4-5.
SHUTTLE TO SHUTTLE CAPTURE



3.2.5 Man/Machine Interface and Control

3.2.5.1 Task Analysis

If practical, it is desirable to have only a single operator control the manipulator. Analysis of manipulator task requirements during space station assembly, cargo handling, berthing, and maintenance operations led to the classification of operator actions given below. On the basis of this analysis it appears that a single operator is, in fact, practical.

Except for emergency use, the operator works under three main control regimens; these are: (a) translation; (b) mating and berthing, and (c) dextrous manipulation. Each regimen imposes somewhat different display/control needs. Accordingly, a three-way partition of function is carried out through the subsequent control concept development. The regimens themselves are defined as follows:

(a) Translation: Movement and orientation of the boom within its available spatial envelope to locate the distal effector near a mating point, or to locate a module (station or cargo) at its berthing point.

(b) Mating and Berthing: Movement and orientation of the distal effector or its load within a restricted spatial region to attach to (or release from) a fixation point on a module, on cargo, on the shuttle, etc.

(c) Dexterous Manipulation: Fine manipulation and/or handling using specialized end-effector(s) on a fixed nearby work surface.

3.2.5.2 Human Factors Analysis

The major human factors problems identified for each of the control regimens are listed below.

(a) Translation:

- 1) Obstacle avoidance in boom movement and orientation
- 2) Slow movement of attached high mass object within dynamic load restrictions of boom and actuators.

- 3) Obstacle avoidance while translating large modules or cargo.
- 4) Minimum time and power expenditure.

(b) Berthing:

- 1) End-effector or module, shuttle, etc. positioning in remote, arbitrarily-oriented coordinate system.
- 2) End connector or special end-effector attachment in 6 DOF fly-by (i. e., shuttle capture).
- 3) Minimum time and power expenditure.

(c) Dextrous:

- 1) Manipulation at remote location within indirect feedback.
- 2) Lack of correspondence between manipulator and operator orientation.

It was concluded that the area requiring greatest design attention is slow translation of large, high-mass objects within tight load and power restrictions. This type of task is not well suited to operator capabilities. Some form of aiding is advisable, and is best supplied by computer means. It was further concluded that with such aiding, manipulator control in the various regimens could be handled by a single operator.

3.2.5.3 Initial Concept Development

Figure 3.2.5-1 presents the preliminary definition of the man/machine interface. Three main subsystems define the operational core; these are: (1) direct manipulator control itself, (2) computer contribution to control and (3) TV displays and generated feedback (the means by which the operator determines manipulator location, orientation, etc.).

Approximately 25 control concepts were generated under three headings (operator oriented, computer assisted, and computer oriented) which reflected varying contributions of the computer element to manipulator control. The systems examined ranged from an entirely manual system to one in which most of the required operations were automatically controlled.

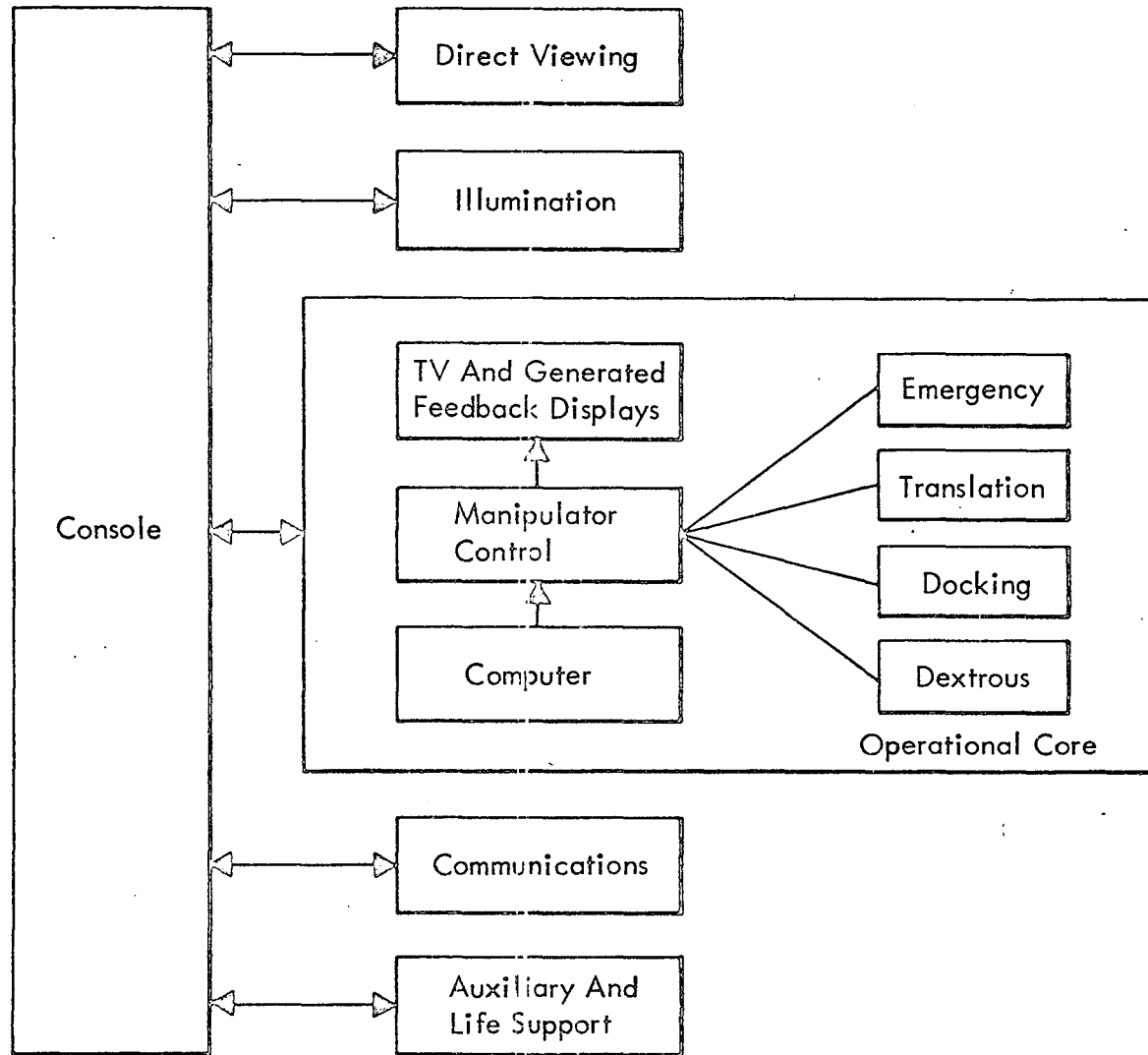
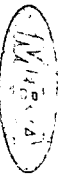
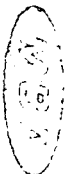


FIGURE 3.2.5-1.
COMPONENTS OF THE MAN/MACHINE INTERFACE

System	Control Mode			Controller			Comments
	Trans-lation	Docking	Dextrous	Trans-lation	Docking	Dextrous	
A							Requires Fulltime Control Of Highly Skilled Operator.
B	Computer-Assisted End-Point			Discrete			Coordinate Trans-formats In Skilled Control Performed By Computer.
C	Computer 'Follower'			Model			Operator Plans And Conducts Trans-lations But Rehearsal Is Possible.
D	Computer Supervisory			Keyboard			Operator Initiates Translations On A Point-To-Point Basis.
E	Computer Stored				Track Sight		Operator Initiates Translations And Docking On A Task Basis.

FIGURE 3.2.5-2.
OPERATIONAL SUMMARY - CANDIDATE SYSTEMS



Five systems emerged as candidate concepts. These are summarized in Figure 3.2.5-2 which defines the allocation of function between the operator and the computer for each major control mode, and describes applicable controllers for the operator's portion of the task. System A, the purely manual concept, was included for purposes of base-line comparison and because some such system will have to be available for emergency backup.

The following paragraphs summarize briefly the system implications of the suggested methods for computer assistance, and also the arguments favoring the various type of controllers.

(a) Computer Assistance Techniques

1) Supervisory Control - The operator gives control commands using a higher-order, symbolic language, such as "Go to 'A'", etc. The computer stores a detailed state space map of the operational environment, interprets the operator commands, determines the required trajectory, and moves the manipulator within the restrictions of load, stopping distance, etc. The technique relieves the operator of responsibility for "on-line" translation of the loaded or unloaded manipulator.

2) Computer Follower - Movements of a small model of the manipulator are stored by the computer and reproduced on the actual manipulator at substantially slower rates. This is a form of supervisory control, substituting analog for digital input. The advantage is that trajectories could be planned and practiced more easily by means of the model than through indexing and equations. In addition, the demands on computer capacity are less.

3) Preprogrammed Tasks - A stored repertoire of completely preprogrammed tasks are executed on operator demand. These tasks might include a series of trajectories and other manipulator operations. In effect, this is the next level of supervisory control, where a simple command initiates a more complex action.

4) End-point Control - The operator's control actions are transformed directly into specified movements of the manipulator end point, instead of movements of the constituent joints. The computer resolves the movements into the signals necessary to coordinate the joints by solving equations-of-state for the manipulator. The advantage to the operator is a high degree of compatibility between movement of the manipulator end-point, and his display/control situation.

Table 3.2.5-1 outlines the requirements on computer performance associated with implementing the above techniques.

(h) Manipulator Controllers

Table 3.2.5-2 briefly summarizes findings regarding the use of discrete, joystick, and master controllers for the type of control required in the Berthing and Dextrous modes. It is assumed that for both discrete and joystick controllers there is a correspondence between position or force at the controller, and a movement rate at the manipulator. In the case of the master controller, there is a direct position-position correspondence between controller and manipulator elements.

3.2.5.4 Feedback Requirements

Table 3.2.5-3 outlines the potential sources of operator feedback associated with the suggested set of concepts. Analysis of these sources in light of other system and station/shuttle requirements produced the following design decisions.

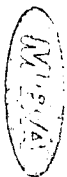
(a) Direct vision will not be included as a primary feedback source, since the operator's console will likely be located in a module of the space station or shuttle, remote from the site of manipulation.

(b) The primary sources of feedback for manipulator movements will be:

- 1) TV for all "on-line" operations
- 2) Digital display for "off-line" and emergency operations

CONTROL MODE	MEMORY STORAGE REQUIREMENTS	SOFTWARE REQUIREMENTS	COMMENTS	AREA OF BEST APPLICATION
Computer Follower	Low (8K)	Real Time Smoothing	Requires a Controller Which Is Geometrically Identical To The Manipulator	Positioning At Unspecified Environment
Computer Assisted End Point	Moderate (16K)	Real Time Vector Transformation	Wrist Orientation Must Be Controlled Through Individual Wrist Actuator Controllers	End Point Rate Control
Supervisory Control	Moderate (Over 20K)	State Space Model Of The Environment	Control Is Limited To Coded Commands. A Code Could Also Be Used To Call In Continuous Rate Or Position Control.	Operation With Transmission Time Delays
Preprogrammed Tasks	High; In Relation To The Number Of Tasks Stored	Programmed Tasks And Programmed Operational Map.	Operation Is Limited To Rigid Tasks.	Operation In Well Defined Predictable Environment

TABLE 3.2.5-1.
COMPUTER REQUIREMENTS





	BERTHING	DEXTRIOUS
DISCRETE (rate)	Despite innate lack of coordination, discrete controls have outperformed rate joysticks for complex positioning and orientation of underwater manipulators, and in other practical applications.	Fine operations under discrete control are reportedly slow and inefficient.
JOYSTICK (rate)	Studies indicate 'multiswitch' rate control can be learned faster, but that performance converges with discrete case after practice. "Master-like" joysticks (CAM) can provide added control-display compatibility, but often fail to do so for some orientations and degrees-of-freedom.	With many joystick designs, inadvertant activation of 'adjacent' motions introduces errors into fine manipulation. Good performance has been achieved on small, quick, pneumatic units.
MASTER (position)	Master has been used successfully in simulated "catches" of lightweight objects in limited, two dimensional regions. Application to longboom manipulators and very high-inertia couplings is uncertain.	Experiment and expert opinion agree that bilateral force reflexive master-slave is optimum controller for restricted dexterous operations.

TABLE 3.2.5-2
CONTROLLER COMPARISON

Information	Modality	Mechanism	Object	Comments
Manipulator Orientation And Location	Visual	Direct Binocular	Overview	Highly Desirable
			Target/Work	May Require Magnification
		TV	Overview	Generally Required For Remote Operations
			Target/Work Area	
			Auxiliary View	Task And System Dependent
		Guide Marks		
		Stored Pictorial	Index Coord's And Trajectories	(Presently In Developmental Stages)
		Generated Pictorial	Distance/Orient To Target	
			Animated Overview	
		Generated Numeric	Joint Angles	Application To Supervisory Control And Backup
			End Point Coordinates	
			Distance/Orient To Target	
Force And Load	Mechanical	Model	Position Reflective	Task and System Dependent
		Master	Position Reflective	
	Visual	Generated Numeric	Force: Out	Redundant If Computer In, May Be Required For Backup System
			Load In	
	Mechanical	Force Reflective	Force Out	Highly Desirable For Dextrous Man, Would Aid Mating
			Load In	
		Sensor	Tactile	Probably Not Necessary
	Audio	Sensor	Contact Motion Loading	Reportedly Helpful, Questionable Whether Worth Including

TABLE 3.2.5-3.
MAJOR FEEDBACK SOURCES

(c) Direct force reflection is essential for dextrous manipulation, but not required for operations with the main boom. Boom forces will be maintained within specified limits by the computer rather than the operator.

Development of the recommended interface control concept is presented in Section 3.3.4.

3.2.6 Visual System

The visual system is the single most important operator feedback loop in the overall manipulator system. Its function is to display the work scene to the operator with all of the resolution, depth cues and geometrical interrelationships necessary so that he can accomplish the required tasks with a minimum of effort, fatigue and physiological strain. Direct viewing (as is done in Apollo docking) can be used in many instances; however, at extended reaches [18.3 m, (60')] the operator will not have sufficient resolution for precise tasks (unless perhaps a bionocular telescope is used) and furthermore, if he must work around or behind obstacles he cannot use direct viewing. Thus a television viewing system is required. Fortunately all of the individual elements of a satisfactory TV system are within the state-of-the-art having either been flown, space qualified, or at an advanced stage of development. The development effort required is mostly for integration. Thus, a television system with remote controlled pan and tilt, focus, variable focal length, color wheel and automatic iris was flown on the Surveyor. A foveal head-aimed system, stereoscopic systems, head mounted displays and eye-aimed systems have been developed separately. The task is to integrate them into an optimized viewing system. The state-of-the-art along with relevant comments on suitable visual system components are given below.

3.2.6.1 Image Tubes. Image tubes with silicon targets that can withstand direct sun illumination without damage, are available from several manufacturers. They have a higher dynamic range than standard vidicons, with a low light level capability one or two orders of magnitude beyond that of standard vidicons, thus reducing the illumination requirements.

Silicon vidicons are preferred over other types of image tubes even though their lag characteristics are inferior because of their increased safety with regard to direct exposure to sunlight. The automatic shutters that non-silicon camera tubes must be equipped with provide the risk of complete camera loss in case of shutter failure. At this writing most major manufacturers are fabricating image tubes with silicon targets.

3.2.6.2 Lens Systems. Lens systems, comprising motorized variable focal length (zoom), focusing and aperture control have already flown. Lenses recently made available incorporating variable neutral density features, greatly increase the dynamic range of aperture control on image illumination (like the Zoomar XB-1 with axial attenuator spot). We propose to incorporate a spring-loaded feature that in case of actuator failure would return the lens to a medium focal length, minimum aperture and hyperfocal distance in order to maintain a basic fixed focus camera capability. Development of a lens system with complimentary focal lengths, near field capability for the foveal-peripheral system is desirable.

3.2.6.3 Display Tubes. Cathode ray tubes of sizes ranging down to 1 inch diameter and 5 inches in length and projection quality brightness and resolution are available, making possible compact rear projection displays. Geometric image distortion in the cathode ray tubes (pincushion distortion) can be eliminated using circuitry recently developed by several manufacturers.

3.2.6.4 Eye Acuity Matching Display Techniques. Both field-of-view and resolution can be considerably improved, while at the same time optimizing bandwidth utilization, by the use of eye acuity matching techniques. The general principle of this technique consists in reproducing the feature of the human eye according to which visual acuity decreases with angle to the optical axis of the eye. This characteristic can be reproduced either by using a single anamorphic lens with variable distortion as proposed by McDonnell-Douglas or a two field system as developed at Control Data Corporation. The two field system is preferable for this application due to the possibility of variable focal length (zoom) that is not present in the anamorphic system. The high resolution, narrow angle field is kept always in the line of sight, matching the resolution of the display to eye acuity. The operator is continuously pointing the camera system in the direction he wants to look at. An example of a two field foveal display is shown in Figure 3.2.6-1.




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FIGURE 3.2.6-1.
FOVEAL AND PERIPHERAL FIELDS AS SEEN
THROUGH CDC HAT SYSTEM

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0062-9999



The low resolution peripheral field is seen only by the low resolution part of the retina in the observer's eye. The observer detects something of interest in his peripheral field and points the cameras so that the detail is seen in the high resolution central field. The foveal display technique attempts to match the display field-of-view to the resolution in the human eye field-of-view, thus reducing waste of bandwidth. In this way, maximum possible resolution for a given bandwidth is always achieved.

For the foveal display technique, the camera system has to be movable. The most advanced way to do it is to slave the camera to the direction of the eye line of sight. Eye direction tracking systems are under development at Honeywell, at the Transportation Systems Center of the U. S. Department of Transportation and at Stanford Research Institute.

3.2.6.5 Stereoscopy. Unambiguous and immediate depth information, essential for the operation of a dexterous manipulator can be generated by stereoscopic display. Stereoscopy is very desirable because of the "empty field" visual conditions and of the lack of familiar depth cues. The art is well known and the components can be easily space qualified. The stereoscopic pair of images can be generated and displayed by use of optical attachments in front of the TV camera and display. The camera attachment comprises a system of reflectors (mirrors or prisms) that split the field of the lens and displace the two resulting halves to the desired stereo base (interocular) distance. A mechanical arrangement is used to adjust the convergence and, if desired, the stereo base. At the display end, the two stereoscopic images are displayed on the two halves of a monitor screen, using image separation optics such as Polaroid filters and mirrors or small angle prisms and lenses for presentation to the eyes. No modifications are needed inside the television system. Controls for changing the aspect ratio of the image, if desired, (e. g., from 3:4 to 1:2 for square stereo halves) can be used in order to provide an optimum image format for maximum transfer of visual information to the observer. MBA has evolved a new split-field stereoscopic TV system that improves stereoscopic acuity and stereoscopic perception by elimination of non-stereoscopic image disparity through 90° field counter-rotation (See Volume IV Simulation Studies).

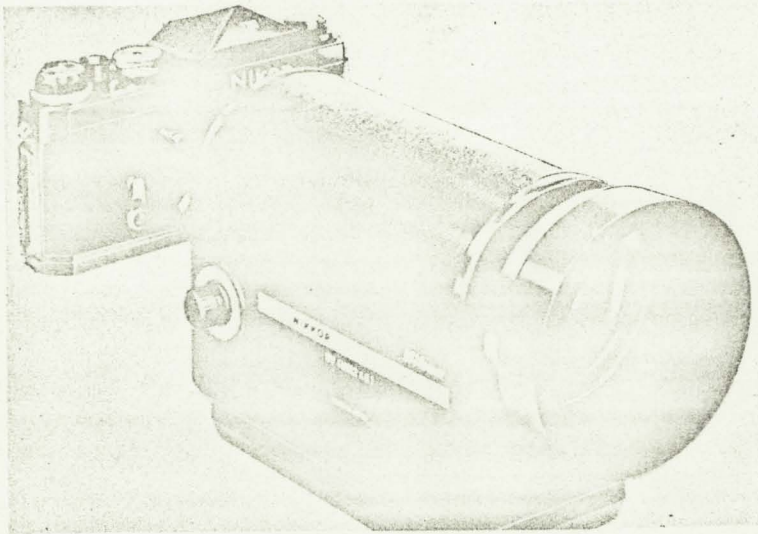
Computer generated stereoscopic depth marks can also be produced on the display for ranging purposes.

3.2.6.6 Resolution. High resolution is desirable for the improvement in detail perception, the speeding up of operator reaction and general operation safety and reliability that it would provide. Components and systems providing resolutions of the order of 1200 lines per frame and up are commercially available at this time. A 5000 line TV system was developed by RCA for an earth resource satellite. However, the bulk of the system is objectionable for the present application.

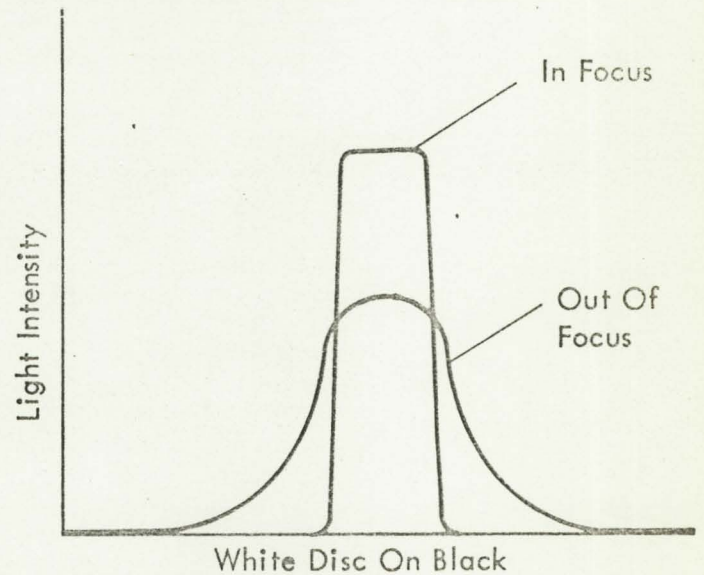
3.2.6.7 Color. Color capability, needed for defect inspection and other special applications, can be provided by color wheel and sequential color image transmission. A color wheel system was flown on the Surveyor lunar mission. The color wheel is preferable to a multiple image tube color TV system because it is intended to be used only sporadically in the present application. It offers less complication and bulk in the camera than the multiple tube, and also does not present advanced development problems for the display.

3.2.6.8 Automatic Focusing and Stereo Convergence Control. Automatic focusing devices are either already commercially available (Figure 3.2.6-2) or in advanced stages of development. An adequate system for television use should use the electrical signals generated by the maximum local light intensities when the image is in focus. (Experiments conducted at CDC by John Chatten showed that the unsharpness produced by the lens either needed to generate the focusing signal cannot be detected by the eye. Automatic focus is very important for short range work, such as dexterous manipulation, where depth of field is reduced and stereoscopic convergence is needed).

The optical axes of the two stereoscopic fields must converge on the focused object. This control could be coupled to the automatic focus control.



Prototype Of Nikkor Automatic Focusing Lens



Shape Of Electrical Signal Produced By Scanning The Image Of A Luminous Disc

FIGURE 3.2.6-2.
EXISTING AUTOMATIC FOCUSING SYSTEM

3.2.6.9 Variable Stereo Base. Varying the distance between the optical axes of the stereoscopic fields makes the apparent depth scale of the observed objects vary. Also, in order to maintain stereoscopic perception of more distant objects, it would be necessary to increase the stereo base. (Stereoscopic perception is a function of the convergence angle). In the present application, a variable stereo base is not needed since dexterous manipulation is done at an established distance from the camera. Also, it would introduce additional mechanical complexity and weight.

3.2.6.10 Camera Mobility. In order to see behind obstructions, it is necessary that the camera can be moved about. A dedicated, mobile boom is recommended to provide at all times a "bird's eye view" as needed.

3.2.6.11 Display and Controls. Display tubes that are already space qualified and of sizes ranging down to one inch are available from a variety of manufacturers. Controls using head-position sensing, eye-direction tracking or isometric, are available to provide the operator with a control of the camera that makes almost no demand on his conscious attention and leaves hands and feet free for other tasks. Techniques useable for stereoscopic vision (such as parallax stereograms and TV scan registration) are already available and will only have to be developed for integration with foveal display and eye aiming controls. (Figure 3.2.6-3 and Figure 3.2.6-4).

A very attractive display consists of a miniaturized optical viewer containing the stereoscope and peripheral display tubes and optics for presenting the images to the eyes. The viewer is supported by a flexible arm with locking features that the operator can position in front of his eyes or remove when desired (Figure 3.2.6-5). An idea of the approximate size of the viewer display elements can be gathered from Figure 3.2.6-6. Pointing control is achieved by a gimbal - type suspension of the viewer so that the operator can point it by pressing with his face on the eye hood. Within an angle of approximately $\pm 20^\circ$, the viewer follows the operator's head motions and the cameras are in a position control mode. Beyond that, isometric controls are used at the stops, with the cameras in a rate control mode with the rotational speed proportional to the pressure

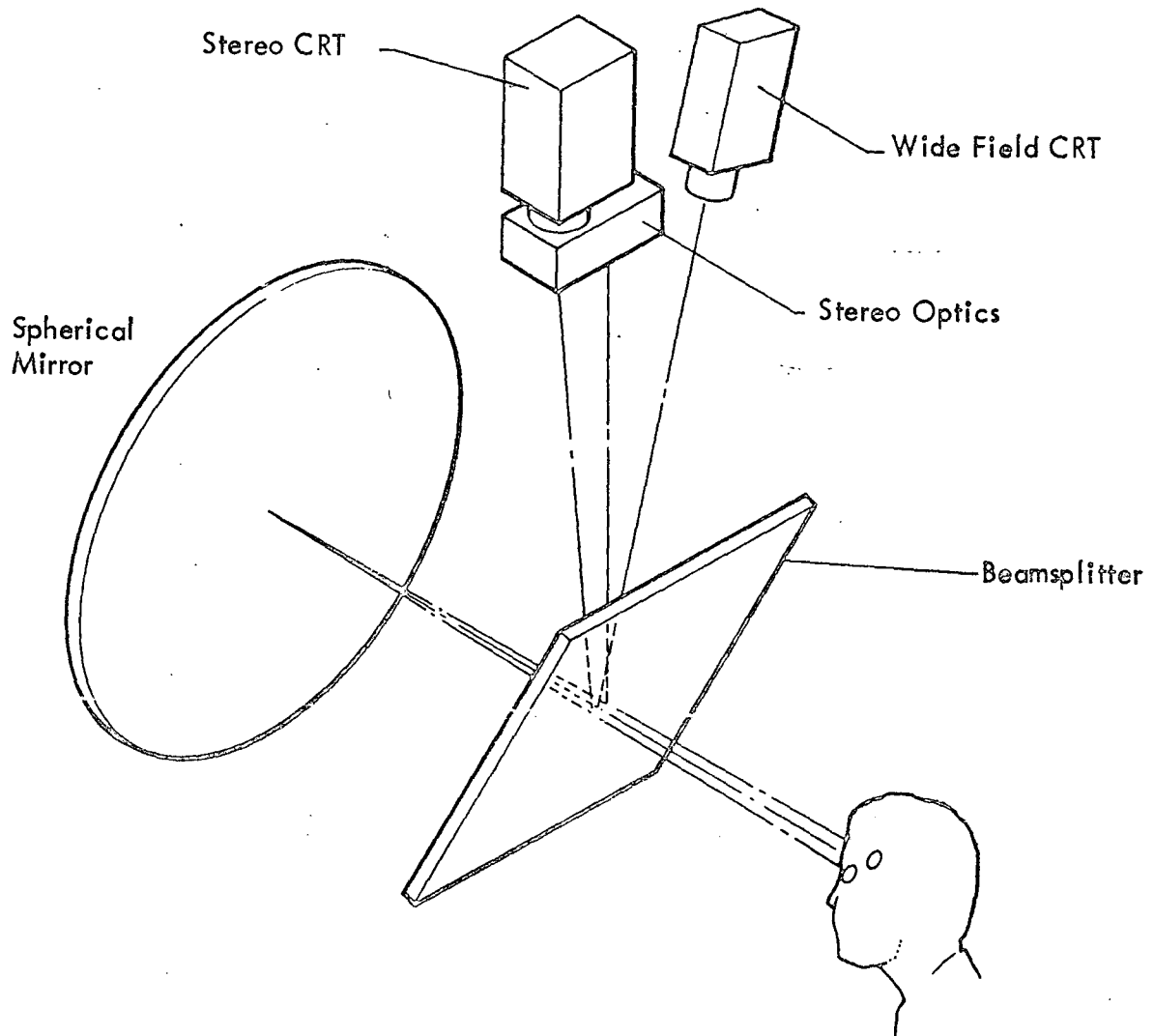


FIGURE 3.2.6-3.
VIRTUAL IMAGE STEREO-FOVEAL DISPLAY

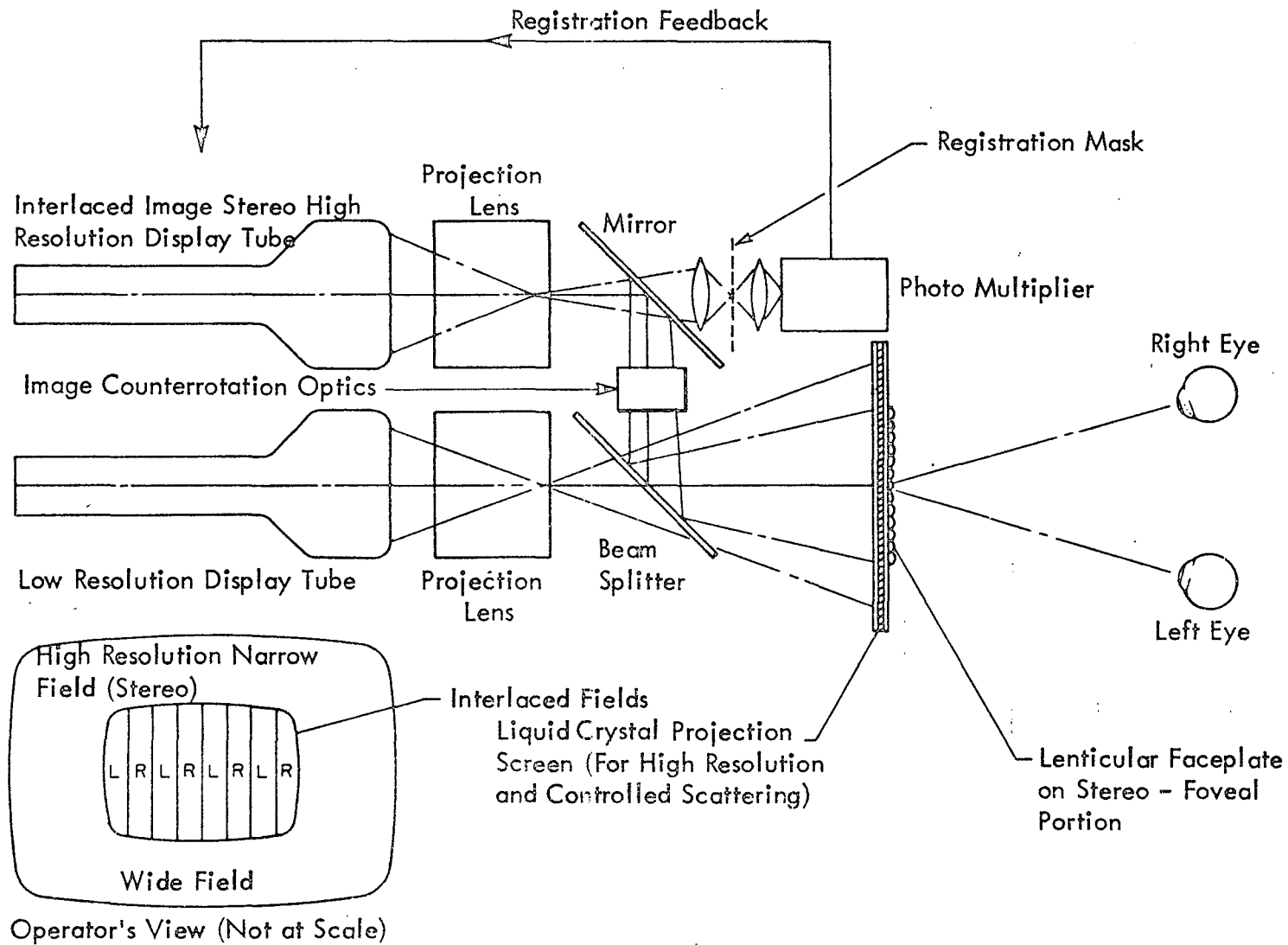
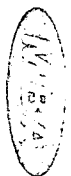


FIGURE 3.2.6-4. REAL IMAGE DISPLAY WITH PARALLAX STEREOGRAM AND INTERLACED LEFT-RIGHT STEREO FIELDS.

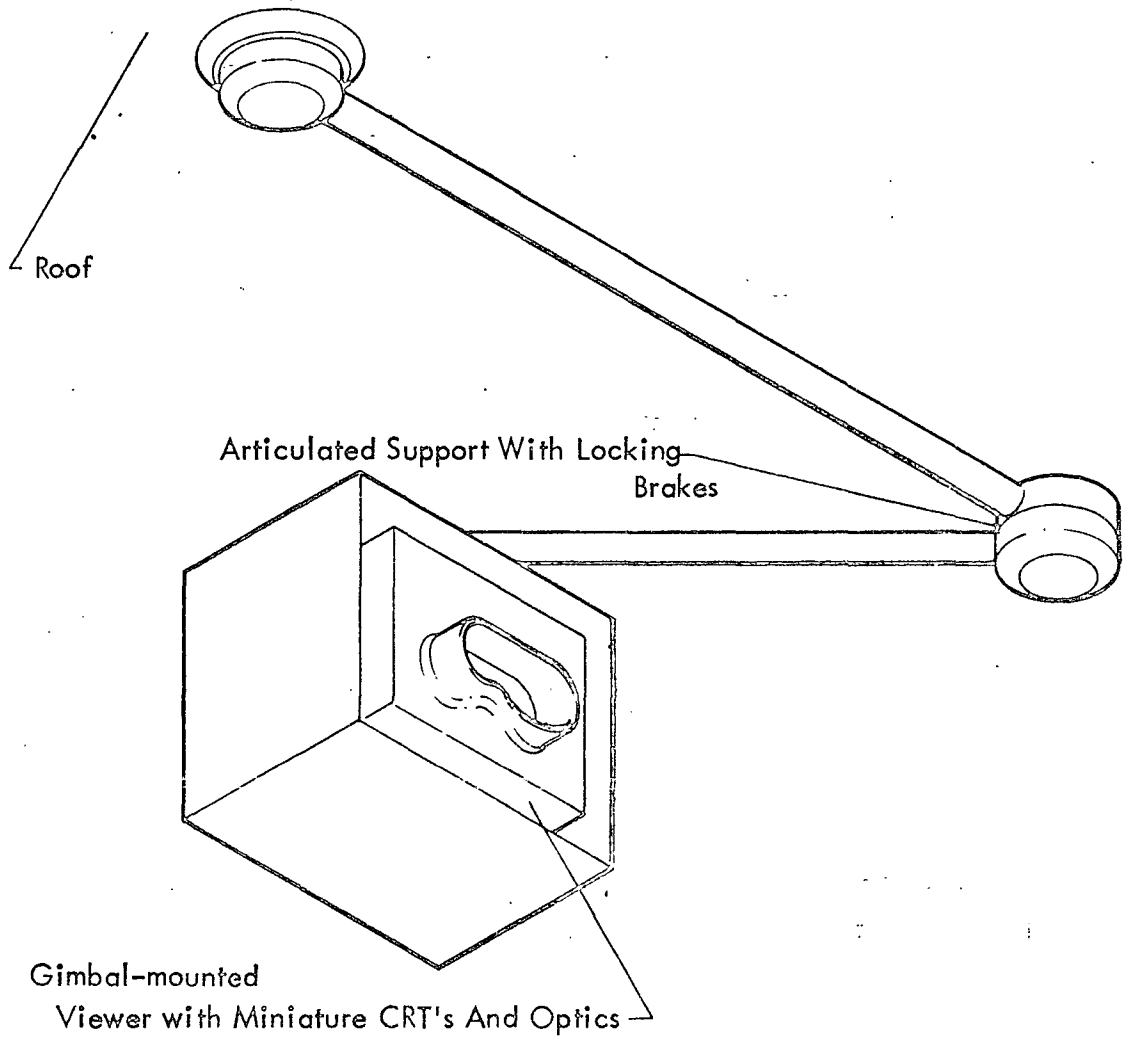


FIGURE 3.2.6-5.
MOBILE VIEWER WITH POSITION-RATE AIM CONTROL

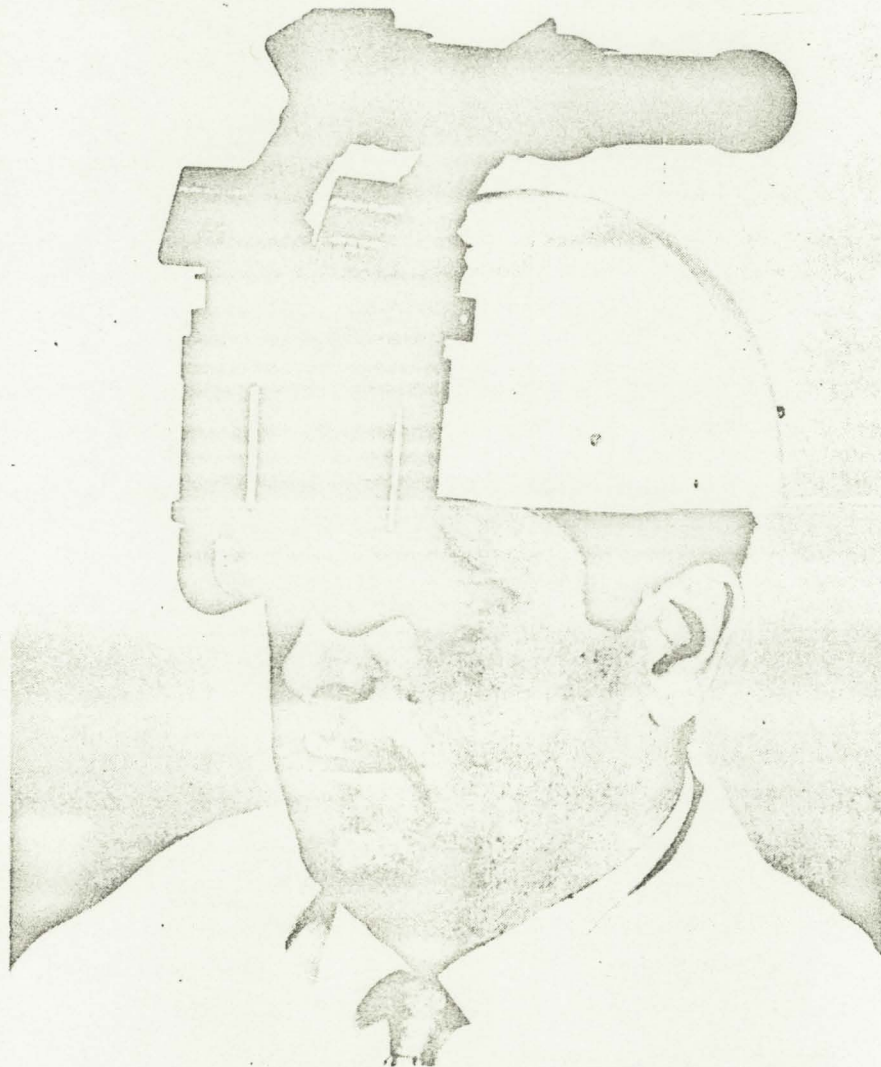


FIGURE 3.2.6-6.
SEE-THRU HEAD MOUNTED BINOCULAR TV DISPLAY

exerted. Such a mobile viewer provides the advantages of miniaturization, optical simplicity, highest quality of the optical image and simplicity of the control function. Furthermore it would require less development effort than a console-mounted display capable of presenting the same visual information.

3.2.6.12 Illumination. The relatively high sensitivity of the silicon vidicon makes illumination in earth shadow a simple problem. Using halogen incandescent lamps, approximately 10 watts/m^2 ($\sim 1 \text{ watt/ft}^2$) of area to be illuminated is needed.

A more difficult problem appears in sunlight, when in the case of shadowed objects, the image tubes cannot accommodate the needed brightness range in the same frame. The shadowed objects must either be illuminated with an intensity of a few percent sunlight (to provide a few shades of gray) or another method must be used.

Artificial illumination providing an intensity of 5 percent sunlight (13,600 footcandles) will require an input of approximately 450 watt/m^2 ($\sim 45 \text{ watt/ft}^2$) of illuminated surface, considering a source beam efficiency of 15 percent for a long life short arc xenon lamp with collector optics.

The same level of illumination can be obtained by using a heliostat with a convex mirror (to get a wide beam of reflected sunlight). The mirror is orientable and servoed to illuminate the field while the space station or shuttle is rotating with regard to the sun, by keeping a position bisecting the angle between the direction of the sun and the direction of the object (Figure 3.2.6-7).

Another possible method of illumination is to use a narrow band filter in front of the camera lens in conjunction with a line light source, such as a mercury vapor arc lamp. In this case, the lamp will have to match sun irradiance only for the filtered region of the spectrum. (Figure 3.2.6-8). With this illumination, the necessary power input is of the order of 100 watts/m^2 ($\sim 10 \text{ watt/ft}^2$).

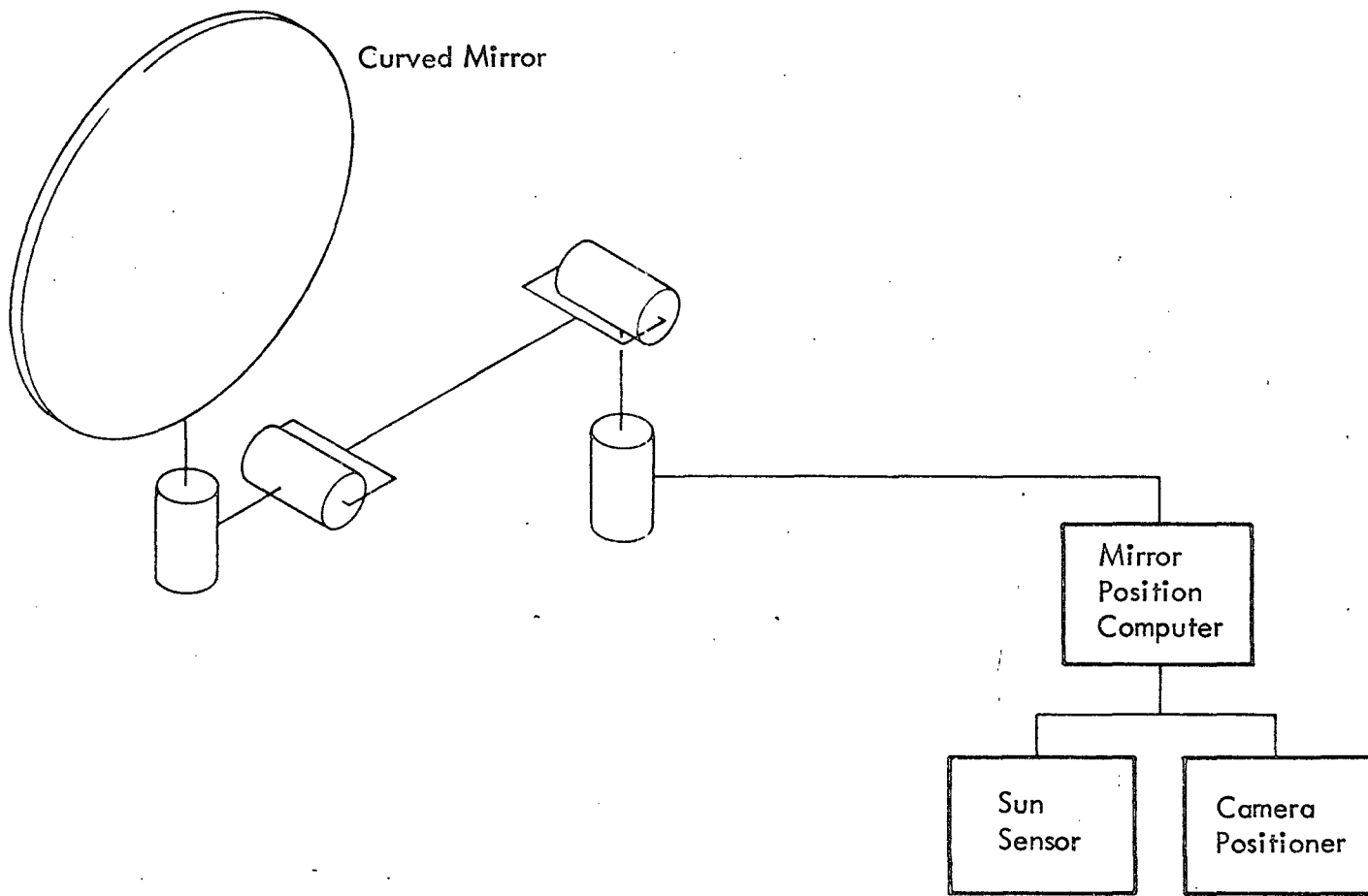


FIGURE 3.2.6-7.
SCHEMATIC HELIOSTAT ILLUMINATOR

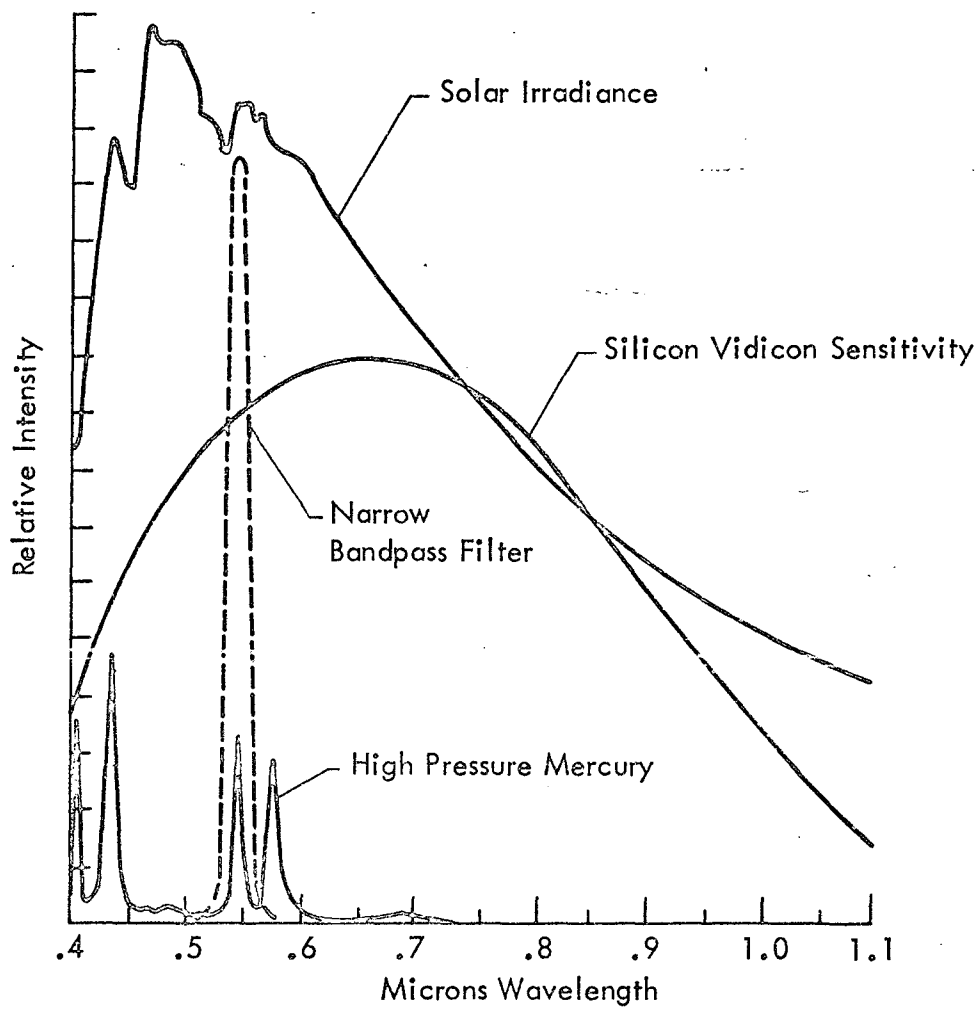


FIGURE 3.2.6-8.
 FILL-IN ILLUMINATION FOR SUNLIGHTED SCENES USING NARROW
 BANDPASS FILTER AND SPECTRAL LINE LIGHT SOURCE

A method whereby there is no need of a light source other than the low intensity one used in earth shadow is made possible by the use of a foveal two camera system. The two cameras are oriented in such a way as to cover the two differently illuminated areas separately so that one camera is used to look at the bright part of the scene, with the other camera covering the dark part.

3.2.7 Control System

Selection of control system equipment is not germane to overall concept selection since state-of-the-art components are involved in all concepts and the control problems are generally the same. The actuators for the joints of the boom must have smooth, slow operation and operate from electrical direct current if possible. A large torque multiplication is required to match the high speed DC motor to the low speed joint. A number of gear systems exist for large numerical speed reduction. An alternate system of hydraulic transmission exists with the possibility of some superior characteristics. The primary mode of control of the boom is rate control. Control of the dexterous end effector is in a conventional position-position, force reflecting master-slave mode.

3.2.8 Data Processing and Transmission

The Data Processing and Transmission system is divided into the following two subsystems, determined by the type of data to be transmitted:

(1) The command and monitor subsystem which handles control signals from the computer-control console to the end control points in the station (or shuttle), and on the boom, such as actuators, lights, camera controls, latches. These signals are characterized by relatively low band widths (1-1000 Hz), low repetition rates and in some cases high accuracy (0.1%).

(2) The video subsystem which has a wide bandwidth (4MHz and up) and moderate accuracy or resolution.

The electronic components required for the Data Processing and Transmission system are state-of-the-art. Essentially all that is required is an engineering development and system integration effort to meet the particular environmental and physical constraints imposed by the total manipulator system and the shuttle or station. A few relevant comments on each of the above subsystems are given below. The space station is considered since it represents the more complex overall system.

3.2.8.1 Control and Monitor Subsystem

A number of systems are able to transmit the data requirements of the teleoperator system. The requirements are not demanding and similar systems are in regular use in space.

A serial pulse code modulation (PCM) system could handle the data. The control points are assigned addresses in serial pulse-time with 10 bits being adequate, and the data to be transmitted is also pulse coded in 10 bits in serial pulse time. The entire control "word" is put in series and multi-plexed with the other addresses and transmitted on a bus. Due to the data rate and number of addresses, the system bit rate is rather high and the bus might have to be coaxial transmission line.

Parallel pulse code modulation transmission is similar to serial PCM but the address is coded on one set of parallel lines and the data coded on another set of lines. The parallel coding reduces the bit rate per line and a bundled wire bus is adequate. Pulse code modulation of signals requires coders and decoders to place the data on the bus and buffer registers to hold the data between multiplex intervals.

Direct transmission of analog data provides a reliable link but requires a large number of wires in the transmission cable, (one for each data channel) and provides an inferior signal to noise ratio.

A light pipe can transmit data on a laser beam at very high rates (wide bandwidth) but presently available fibers have a large attenuation.

A comparison of the electronic transmission systems is presented in Figure 3.2.8-1. It is apparent that the weight of any of these systems is second order and that a particular system can be chosen on the basis of complexity, capability, growth potential and cost. On this basis the PCM system is the best overall concept.

3.2.8.2 Video Subsystem

The anticipated video signal requires for the main boom and dexterous anthropomorphic end effector are given in Figure 3.2.8-2. The television video signal distribution system could be a modulated radio frequency electro magnetic radiation system. The independence of wire and cables is desirable. However, the changing nature of the propagation path due to station configuration changes and to movements of the boom about the station and shuttle render it impractical.

Television signal transmission is possible by a single cable through the station with jumpers installed on unused terminals, cameras and monitors on the ends. The simple cable system is desirable but the maintenance of matching with jumpers is undesirable.

	Weight Per Module	Weight Per Boom	Flexibility/ Expansion Capability	Complexity	Cost of Parts	Station Control Compatibility
1. Serial PCM 1 Coax	.22 Kg + .0144 Kg/m (1# + .02#/Ft)	.66 Kg + .0144 Kg/m (3# + .02#/Ft)	Yes	High	Med + \$20,000/Arm	Possible
2. Parallel PCM 20 Wires	.33 Kg + .028 Kg/m (1.5# + .04#/Ft)	.22 Kg + .028 Kg/m (2# + .04#/Ft)	Yes	Med	Med - \$16,000/Arm	Yes
3. Analog 200 Wires	.44 Kg + .28 Kg/m (2# + .4#/Ft)	.28 Kg/m (.4#/Ft)	No	Low	Low \$3,000/Arm	No

FIGURE 3.2.8-1.
COMPARISON OF CONTROL & MONITOR DATA TRANSMISSION
SYSTEM FOR THE SPACE STATION



NAME	COLOR	B/W	RATE (FRAME/SEC)	P/T	STEREO
1. WRIST	B/W	4 MHZ	30	NO	NO
2. FOREARM	B/W	4 MHZ	30	NO	NO
3. UPPER ARM	B/W	4 MHZ	30	NO	NO
4. SHOULDER	B/W	4 MHZ	30	NO	NO
5. "HEAD	Color	4 MHZ	30	YES	YES

FIGURE 3.2.8-2.
TV SIGNALS GENERATED ON THE MAIN BOOM AND DEXTEROUS END EFFECTS



A system of parallel coaxial transmission lines is possible with switching matrices at the junction points (station modules) to maintain impedance match. There would be as many coaxial cables as there are cameras. This would be a low loss, high signal-to-noise system.

A coaxial transmission system with parallel terminals but without switches is possible by substituting passive splitters to achieve the impedance match. The signal attenuation would be rather high but could be made up with amplifiers in each station module. The direct disadvantages are additional weight, complication and power consumption.

3.2.9 Environmental Control and Life Support

In order to insure that the crew can function in the manipulator module, it must contain Environmental Control and Life Support Systems (EC/LSS). However, this module can be operated in three different modes so the EC/LSS equipment must necessarily be adequate for each.

(1) Attached Operation - The module is attached either to the space station or the shuttle. As such it is able to draw upon the EC/LSS systems of its support vehicle. This will be the standard mode of operation and is expected to exist about 99% of the time.

(2) Independent Operation - Independent module operation would occur when the module is being transferred from one location to another. The modules would be manned during this transfer operation. The maximum duration of such a transfer would be six hours. Less than 1% of the total mission is anticipated to be spent in this mode.

(3) Emergency Operation - During the independent operations, emergencies could occur which would necessitate the evacuation of the module with an E.V.A. maneuver in order to get back to safety. Emergencies such as malfunctioning berthing systems or module leaks can be envisioned.

During the attached operation, the EC/LSS equipment could be quite simple. Sustaining the correct pressure in the module is trivial since a direct connection with the space station has been made. A resupply of O_2 gas and the return of CO_2 could be done with a simple fan which would guarantee proper circulation. This would also assure circulation of the N_2 gas.

The forced circulation would have the added benefit that it would aide in the cooling of the module atmosphere. If the cooling of the operator(s) could not be done this way, heat exchangers, water separators and cooling lines would have to be added.

For the independent operation, the equipment becomes much more complicated. The EC/LSS can be either open or closed loop or a combination of the two. Existing Apollo & LEM Type hardware could be used to keep the cost low.

In order to keep the equipment simple and lightweight, an open loop air supply system could be used. This would consist of rechargeable air bottles which would be bled into the module through a pressure regulator. A relief valve would cause the air to leak out of the module at a pre-determined rate causing "fresh" air to enter. This system would keep the pressure, O_2 and N_2 at pre-determined levels. The flow rate would be set so as to keep the CO_2 percentage below a safe level.

The same objective could be accomplished with much more sophisticated and expensive equipment, using a closed loop system. The air supply could come from separate O_2 and N_2 bottles. Regulators and detectors would be needed to assure the proper mix ratio. The CO_2 could be removed with LiOH scrubbers like those used in the Apollo Spacecraft. However, such a system is not required. Heat exchangers, water separators and cooling equipment would be required to prevent the manipulator operator from dehydrating.

The Life Support Equipment for the emergency mode would require a complete pressure suit. This could be a closed loop system as was used for the lunar back pack or an open loop purge system similar to the back up system on the back pack. This back up system could be used since failure of it would constitute a double failure.

The emergency system would have to be modified to allow the use of 14.7 psi air but this would be done for the EVA suits for the Shuttle and Space Station anyway.

The problem of waste management is easily solved. For the attached case, the manipulator operator could return to the Space Station and use the facilities there. During the independent mode, Apollo type collection bags could be used. For the emergency case, collection bags would not be required because of the short duration of the emergency.

3.2.10 Materials

3.2.10.1 Introduction

For space applications, the typical approach for materials selection has been to compare strength to density and modulus to density ratios. Although this is clearly inadequate from the standpoint of long term reliability (e. g., fatigue, fracture mechanics, and radiation considerations), as a preliminary screening method they are reasonably good estimates of how a long tubular member might respond to static and dynamic loads. The selection philosophy is based upon existing attainable properties and not those potentially possible. In this way the current desirability of exotic materials may be more realistically assessed. Certainly, prime candidates for a long, stiff tubular beam are composite materials. For comparison a number of possible configurations are listed as follows:

1. Homogeneous material
2. Unidirectionally reinforced fibrous composites
3. Cross-plyed reinforced fibrous composites
4. Thin-film laminated sheet composites
5. Various combinations of above

For the preliminary screening, several typical high strength aluminum, titanium and steel alloys have been picked. Also, a number of fibrous composites were selected, typical of the best metal and epoxy matrix composites available today. Here, only the longitudinally oriented fibrous composites are initially listed, although it is realized that this gives an unrealistically biased view of their potential. Finally, a relatively new development of laminated thin-film composites is also included. Combinations of these were not considered at this time although it must be recognized that this approach may give the optimum combination of desirable properties. The preliminary screening will allow two materials to be chosen from each class. These will then be subjected to a more detailed tradeoff study.

3.2.10.2 Preliminary Screening

As noted in Table 3.2.10-1, the strength to density and modulus to density are listed for each material. For the homogeneous materials, with the exception of beryllium; there is little choice with respect to modulus to density, the value typically being $2.54 \times 10^8 \text{ m}$ (10^8 in). The dynamically strain-aged Ausformed H-11 steel and the Grade 400 maraging steel are decidedly superior to the aluminum and titanium alloys with respect to strength to density. However, there would be considerable difficulty in manufacturing and joining a dynamically strain-aged Ausformed tube that had a strength near $2.76 \times 10^9 \text{ Pa}$ (400 kpsi) For this reason, the preliminary selections of homogeneous materials are 6Al-4V titanium Grade, 400 maraging steel, 7075-T6 aluminum and beryllium. The large stiffness to weight ratio (modulus to density ratio) for beryllium justifies serious consideration of its use.

With respect to the unidirectional composites, it may first be noted that the metal-matrix composites come fairly close to achieving their calculated strength potential except in the case of Ti-B which has a compatibility problem. The compatibility problem is further seen in the modulus comparison where the boundary layer of TiB_2 contributes greatly to the elastic modulus. The selected metal matrix composites are Al-B and Al-graphite (Thorne! 50) which are relatively comparable in both strength and modulus to density. For the epoxy-base composites, it is significant that the observed composite strengths are considerably less in most cases than the calculated ones. Considering the disparity between the calculated and observed composite strength of epoxy-graphite, this probably has the best long range potential of all the epoxy-based composites. Observed strength and modulus to density ratios give epoxy-boron and epoxy-graphite the best rating of all epoxy-based composites.

MATERIAL		Ultimate Strength 10 ³ psi		Young's Modulus 10 ⁶ psi		Density Lb/in ³		Composite Strength (0.5V _f) 10 ³ psi		Composite Modulus (0.5V _f) 10 ⁶ psi		Strength To Density Ratio 10 ⁶ IN.	Modulus To Density Ratio 10 ⁷ IN.
		Matrix	Fiber	Matrix	Fiber	Matrix	Fiber	Calc.	Obs.	Calc.	Obs.		
HOMOGENEOUS:													
7075-T6 Al	-	80	-	10.5	-	0.101	-	-	-	-	-	0.79	10.4
6AL-4V Ti	-	160	-	16	-	0.160	-	-	-	-	-	1.00	10.0
4340 Steel	-	300	-	29	-	0.283	-	-	-	-	-	1.06	10.2
Ausformed H-11 Steel (a)	-	400	-	29	-	0.283	-	-	-	-	-	1.41	10.2
Grade 400 Maraging Steel	-	400	-	29	-	0.290	-	-	-	-	-	1.38	10.0
Beryllium	-	60	-	44	-	.067	-	-	-	-	-	.90	60.0
UNDIRECTIONAL COMPOSITES:													
(Metal Matrix)													
AL	B	35	450	10.5	55	0.101	0.096	242	183	32.7	33.2	1.86	33.7
AL	Stainless Steel (b)	68	450	10.5	29	0.101	0.290	259	255	19.7	21.0	1.31	10.8
AL	Graphite (Thornei 50)	35	350	10.5	47	0.101	0.056	192	160	28.7	-	2.04	36.5
Ti	Be	110	185	16	44	0.160	0.067	142	148	30.0	32.0	1.31	28.2
Ti	B	110	450	16	55	0.160	0.094	280	140	35.5	41.5 ^c	1.10	32.6
UNDIRECTIONAL COMPOSITES:													
(Epoxy Matrix)													
Epoxy	B	10	450	0.5	55	0.040	0.096	230	190	27.7	30.8	2.79	45.3
Epoxy	E-glass	10	400	0.5	10.5	0.040	0.092	205	132	5.5	5.5	2.00	8.4
Epoxy	S-glass	10	500	0.5	12.6	0.040	0.090	255	192	6.5	6.7	2.95	10.3
Epoxy	Silica	10	700	0.5	10.5	0.040	0.079	355	171	5.5	-	2.92	9.4
Epoxy	Si C	10	300	0.5	65	0.040	0.120	155	-	32.7	-	1.94	40.9
Epoxy	Graphite (Thornei 50)	10	350	0.5	47	0.040	0.056	180	101	23.7	20.9	2.10	43.5
LAMINATED SHEET COMPOSITE:													
Ti	B ₄ C	110	330	16	65	0.160	0.091	220	140	40.5	40	1.12	31.8

TABLE 3.2.10-1.
MATERIAL PROPERTIES - PRELIMINARY SCREENING



Finally, the one laminated sheet composite appears very promising since it has a modulus to density ratio approaching the best metal-matrix fibrous composites. Although the strength to density is not particularly high, one should keep in mind that this laminated composite already has planar isotropy so that no cross plying is necessary. As will be seen in the more detailed tradeoff study, the necessity of cross plying greatly detracts from the potential of fibrous reinforced composites.

3.2.10.3 Initial Tradeoff Study

The approach utilized was essentially that of Cole and Cervelli, who characterized the structural efficiency rules of composite and homogeneous both experimentally and analytically.

The appropriate parameters are -

(1) Weight Index:

$$W = Dtp$$

where W is the cross-sectional weight per length, D is the diameter of the tube, t is the thickness and p is the inactive density.

(2) Compressive load:

$$P_c = \pi k_3 \sigma_c D^2$$

where P_c is the critical failure load in compression σ_c is the compressive ultimate strength and $k_3 = t/D - (t/D)^2$.

(3) Buckling Load:

$$P_{cr} = 4\pi^3 E \omega^4 k_3 / L^2 k_2$$

where P_{cr} is the critical buckling load, E is the modulus of elasticity, L is the length of the column, ω is the radius of gyration which is approximately $0.353D$ for a thin-walled tube, and $k_2 = 1/2 - t/D + (t/D)^2$

(4) Bending:

(a) Load Index -
$$P_{bc} = \pi k_1 \sigma_b D^3 / 2L$$

where P_{bc} is the critical failure load in bending,

σ_b is the bending ultimate strength and $k_1 =$
 $t / 2D - 3(t/D)^2 + 2(t/D)^3$

(b) Deflection Index -

$$\delta = P_b L^3 / 3EI$$

where P_b is the bending load and I is the moment of inertia.

(5) Torsion:

(a) Load Index

$$T_c = \sigma_{st} J / C$$

where T_c is the critical torque, σ_{st} is the torsional clear strength, J is the polar moment of inertia and C is the distance from the neutral axis.

(b) Twist Index -

$$\theta = TL / G_{xy} J$$

where T is the applied torque, and G_{xy} is the shear modulus of elasticity.

A few points of discussion are in order. First, only 7075-T6 aluminum, 6AL-4V titanium, the AL-B, epoxy - B fibrous composites and the Ti-B₄C laminated composites were evaluated. Beryllium was not included in these comparisons because of lack of definitive stress/fatigue/crack sensitivity data pertinent to the anticipated loading historys for the present application and because the overall attractiveness of Beryllium will depend on a detailed structural design taking into consideration practical, state-of-the-art fabrication methods. However, because of its high stiffness to density ratio it is given further consideration in Volume III "Concept Analysis".

To eliminate any preconceived notions, a rating system was devised prior to the assessment of the individual materials. First, a single geometry was considered, that of a tubular member 18.3 m (720 in) long with a diameter 20.3 cm (8 in) and a thickness of 2mm (0.080 in) so that $D/t = 100$. For the deflection and twist indices, it is meaningless to consider critical bending loads or torques for failure, since at this point the tubular member would look like a pretzel. As an alternative, arbitrary loads of 45 kg (100 lbs) in bending and 2250 Nm (20,000 in-lb) of torque were chosen. At this force, it was not considered feasible to assess all possible composite wrap configurations and so three typical ones were chosen: unidirectional, $0^\circ - 90^\circ$ cross ply and $45^\circ - 45^\circ$ cross ply. The average of these three systems should give a rough idea of how current multi-ply composite systems might perform.

Utilizing data from the references in Section 4.0, the data given in Table 3.2.10-2 were determined. For a structural efficiency rating, rather than dividing each load or deflection by the weight index, the weight per unit length was assessed at a value six times as large as all other parameters since six parameters are dependent on the section size. The material with the best property for all other criteria was arbitrarily given a rating of one and the others were proportioned appropriately.

From the weighting noted in Table 3.2.10-3, it is seen that besides the structural considerations, weight was given to manufacturing and joining techniques. This partially due to the cost considerations, partially to time considerations and partially due to the possible degradation of performance due to joining. Comparing the worst to the best case, the total structural weight savings for a 18.3 m (720 in) long tubular member would be about 59 kg (130 lbs). It would not seem that the marginal gain in weight provided by epoxy-B would be sufficient to justify the larger expense of developing the processing, fabrication and joining.* Furthermore, if the weight advantage were ignored, the epoxy-B would rate little better than most homogeneous materials on an overall basis.

* Although these methods have been reasonably well developed, the testing stage for jumping from advanced development to hardware would be considerably more expensive and time consuming than if 6AL-4V Titanium or 7075-T6 Aluminum were utilized.

	7075-T6	Homogeneous 6Al-4V Ti	Fibrous Composites						Laminate Composite Ti-B ₄ C
			Al-B			Epoxy-B			
			UD	0°, 90°	45°, 45°	UD	0°, 90°	45°, 45°	
Weight/Unit Length, lb/in.	0.202	0.319	0.196	0.196	0.196	0.136	0.136	0.136	0.250
Compression, 1000 lbs.	160	299	321	200	46	440	300	28	280
Buckling, P _{CR} , 1000 lbs.	3.08	4.69	9.7	6.13	7.6	9.0	4.84	1.14	11.7
Bending, P _{b max.} , Max. Load, 1000 lbs.	0.43	0.81	1.35	0.30	0.16	1.35	0.65	0.16	0.76
100' Deflection at 100 lbs., inches	74	49	23.7	37.6	30	25.5	47.5	206	19.6
Torsion, T _{max} , Max. Torque, 1000 in.-lbs.	410	825	115	119	1000	115	115	670	700
20,000' Twist at 20,000 in.-lb., degrees	6.5	4.05	3.26	4.4	2.7	8.6	13.3	3.4	1.7
Fatigue Limit at 10 ⁷ cycles, 1000 psi	40	80	80	45	20	90	48	22	70

TABLE 3.2.10-2.
MATERIAL TRADE OFF DATA



3.2.10.4 Lubrication

The space shuttle/station teleoperator is required to operate reliably over a long period of time in a harsh environment. The rotating elements require lubrication. The sliding contacts require antisiezing treatment for use in vacuum. The electrical contacts require treatment for reliable conductivity, low wear and resistance to cold welding. A variety of materials are available for use over wide temperature ranges and in vacuum. For sleeve, flange and thrust bearings, there are plastic materials. Dixon Corporation makes Rulon and Teflon usable from -240° to $+288^{\circ}\text{C}$ (-400° to $+550^{\circ}\text{F}$). The dry bearings are compatible with aluminum and usable in vacuum. DuPont makes Vespel and Delrin which are similar and could be used for no maintenance bearings. To eliminate siezing and cold welding, a dry surface treatment would be desirable. Lubrication Science, Inc., produces Dicronite, a dry, surface treatment of tungsten disulphide that can be applied to most any surface. Ball Brothers Research Corporation also produces a surface treatment of VacKote for the same application. To lubricate heavily loaded bearings for use in vacuum and over a wide temperature range, a low vapor pressure oil or grease is required. There are a number of sources; Ball Brothers Research Corporation, VacKote, DuPont Krytox and Bray Oil Company's Brayco. All have been used in space previously. Electrical contact treatment has been done by Ball Brothers Research Corporation by the VacKote process and is a very important and essential part of the vacuum and long duration operation conditioning process.

3.2.11 Technology

The Shuttle and Space Station Manipulator System for assembly, docking, maintenance and cargo loading can be developed with current technology. A considerable amount of equipment is available off-the-shelf and some of the equipment is "space qualified" by past successful operation in space.

Items requiring development are:

- (1) The walking boom in an overall sense is a new concept. However, the only really new features, compared with a conventional boom, is the electro-mechanical end connector which enables the boom to repeatedly connect either end of the boom with mating root points about the station and shuttle and with other end effectors. A substantial electrical connector technology exists, including vacuum type connectors, however, detailed design, development and testing of these particular end connectors is required to achieve a highly reliable, long life unit.
- (2) The actuators as an assembly are new, however, the components are well proven. The rates and torques are rather uncommon and detail design, fabrication and testing in vacuum is necessary.
- (3) Operation of the complete boom assembly at full scale in simulated zero-g is mandatory to assure full capability in use.
- (4) Dynamic control of boom flexibility is feasible for the primary vibrational modes but a study should be made to determine the adequacy or need for this control.
- (5) The stereo-foveal color TV display system has never been assembled as a complete system and will require detail design, fabrication and testing.
- (6) A narrow band illumination light source (Mercury high pressure short arc) could be developed to provide illumination with less expended electrical power than the broad spectrum sunlight fill-in illumination. This system would have to be developed for the rather unique requirements of the space station or shuttle. However, the use of a dual field foveal system may eliminate any requirement of sunlight fill-in lighting. The feasibility of this technique must be determined.

(7) Lubrication of bearings, joints and sliding contact for operation in a vacuum will be required for full performance. There are a number of commercial sources of lubricants and this is not expected to be a controlling problem, but the designs will have to be tested for vacuum operation.

(8) The wide range of operational requirements place demands on the man/machine interface beyond current manipulator experience. Mock up and simulation studies of the complete man/machine interface including computer assisted supervisory control are required. These studies should also include evaluation of visual displays to establish the necessary human factor and performance requirements for both direct and video systems.

	7075-T6 Al	6Al-4V Ti	Al-B			Epoxy-B			Ti-B ₄ C
			UD	0°, 90°	45°, 45°	UD	0°, 90°	45°, 45°	
Weight	4.05	2.56	4.15	4.15	4.15	6.00	6.00	6.00	3.26
Compression	0.36	0.68	0.73	0.45	0.10	1.00	0.68	0.06	0.64
Buckling	0.26	0.40	0.83	0.52	0.65	0.77	0.41	0.09	1.00
Bending	0.32	0.60	1.00	0.22	0.12	1.00	0.48	0.12	0.56
Torsion	0.27	0.40	0.83	0.52	0.65	0.77	0.41	0.10	1.00
	0.41	0.82	0.11	0.12	1.00	0.12	0.12	0.67	0.70
Fatigue	0.26	0.42	0.52	0.39	0.63	0.20	0.13	0.50	1.00
	0.45	0.89	0.89	0.50	0.22	1.00	0.53	0.25	0.78
Manufacture	1.00	1.00	0.60	0.60	0.60	0.80	0.80	0.80	0.60
Joining	1.00	1.00	0.80	0.80	0.80	0.60	0.60	0.60	0.80
TOTAL	8.38	8.77	10.46	8.47	8.92	12.26	10.16	9.19	10.34
AVG. TOTAL	8.38	8.77	9.28			10.50			10.34

TABLE 3.2.10-3.
MATERIAL WEIGHTING TABLE



3.2.12 Utility

A detailed utility analysis is not required for evaluation and selection of a preferred manipulator concept. It is sufficient only that the selected concept have the potential to accomplish the desired tasks as readily as other concepts. Some general considerations on space manipulators relevant to concept selection are given below.

Primary operations (tasks) of the subject manipulator are of two distinct types: 1) large object handling and 2) maintenance. Large object handling in a zero gravity environment is a completely new use for a manipulator, however, its feasibility has been demonstrated by simulation studies performed by several investigators. Goertz demonstrated capture of a tumbling, small satellite size object, (dimensions on the order of 1 m ($\sim 3'$)) with a pair of force reflecting manipulators (2 arms). It was shown that force reflection provides a means of decelerating masses where frequencies (tumbling, mass spring oscillations) are within man's ability to react (a few Hertz). Workers at G. E. and elsewhere have successfully demonstrated capture operations using single boom, large objects (discussions of several meters) and plug in type end effectors in a 3-dimensional air bearing for simulation facility. Successful berthing simulations have likewise been accomplished.

A large body of experience has been accumulated on repair and maintenance type operations in hot cell activities throughout the world. A zero gravity environment will not cause any fundamental difficulties with such operations because they are generally accomplished with relatively small (man-size) dexterous, force reflecting manipulators in intimate contact with and vicinity of the work piece. Zero gravity is of concern only to the extent that a means must be provided to restrain the manipulator and work objects (by, say, a grappling arm) and to prevent parts and tools from escaping or "floating away". In fact a zero gravity environment may be advantageous in some ways. For example the strength of the dexterous manipulator need only be sized on the basis of the forces required to operate tools, push parts together or pull them apart, e. g. - the weight of heavy masses is of no consequence such as it would be on earth.

Emphasis in the present study has been placed on shuttle berthing, station assembly and cargo handling operations with general maintenance and propulsion package replacement as secondary. As discussed in Section 2.0 "Summary" and 3.2.2 "Boom Configuration", a single manipulator boom has been chosen for the recommended system. A small scale model of the manipulator system, space station and shuttle crew compartment and cargo bay was used to study the reach and accessibility capability of the manipulator. It was established that the single boom system can accomplish shuttle berthing, station assembly and cargo handling without any special end effectors, i. e., the end connector on the boom is adequate for capture and engagement for all such operations. For other operations, say for example, propulsion package replacement, special end effectors may be required. The type of end effector will depend on details of the propulsion package and connector designs. Consideration must also be given to tool and parts holders. The manipulator control module can be used to store end effectors, tools, cabinets, etc. The distal end of the boom and/or end effector has the capability of reaching down to interchange items stored in the module.

For shuttle applications the external control module would not be used: rather, the boom would be plugged into a root point on the shuttle and control would be accomplished from within the shuttle. Auxiliary devices, or even perhaps another boom, may be required depending on the specific task to be performed and on details of the shuttle design. If a berthing port is always available to restrain (and possibly rotate) the object being operated on, then most, if not all, tasks could be accomplished with a single boom and appropriate end effectors. If it is not permissible to berth the object on the shuttle (for example because of possible local outgassing which might contaminate optical systems) an auxiliary boom will be required. However, since the auxiliary boom's function may only be to hold and rotate, it can be made much simpler and lighter than the primary boom. The requirements of each task must be examined and the appropriate auxiliary devices carried along for that particular mission.

Concept Selection

The results of the Phase I analyses and the recommended manipulator concept (see Section 2.0 "Summary") were presented at a briefing to NASA personnel at MSC, Houston, Texas on 30 August 1971. Full details of the presentation are summarized in MBA Briefing Aid document MB-R-71/85. Upon review and analysis of the briefing and supporting documentation NASA MSC approved MBA's recommended concept with the following options selected:

- 1) An internal control station without direct viewing shall be used.
- 2) A panel display shall be used rather than a mobile viewer so as not to encumber the operator.
- 3) No portable control stations are to be used.

In addition, MSC established the following ground rules:

- 1) The total manipulator system weight, including the auxiliary lighting boom, shall not exceed 454 Kgms (1000 lbs). The weight of additional root points are not charged against the manipulator system.
- 2) The boom diameter shall be $\leq .229$ m (9") to facilitate stowage in the shuttle.
- 3) A light weight metal such as aluminum or titanium shall be used. Composite materials are not to be used because of their high development costs.
- 4) The station modules [11,340 Kgm (25,000 lbs)] are to be the design drivers. It can be assumed that immediately after capture, the shuttle control system can bring the shuttle kinetic energy down to values lower than for moving modules. Specifically the boom shall be able to catch and hook up with the shuttle while it is moving at .12m/sec (.4 ft/sec) but at this speed it only has to relay angle changes and velocity data to the shuttle. The shuttle will decrease its speed to .03m/sec (.1 ft/sec) using its own maneuvering units at which time the manipulator must be able to take out any remaining velocity.

- 5) The 040A shuttle configuration can be used as the reference for the study.

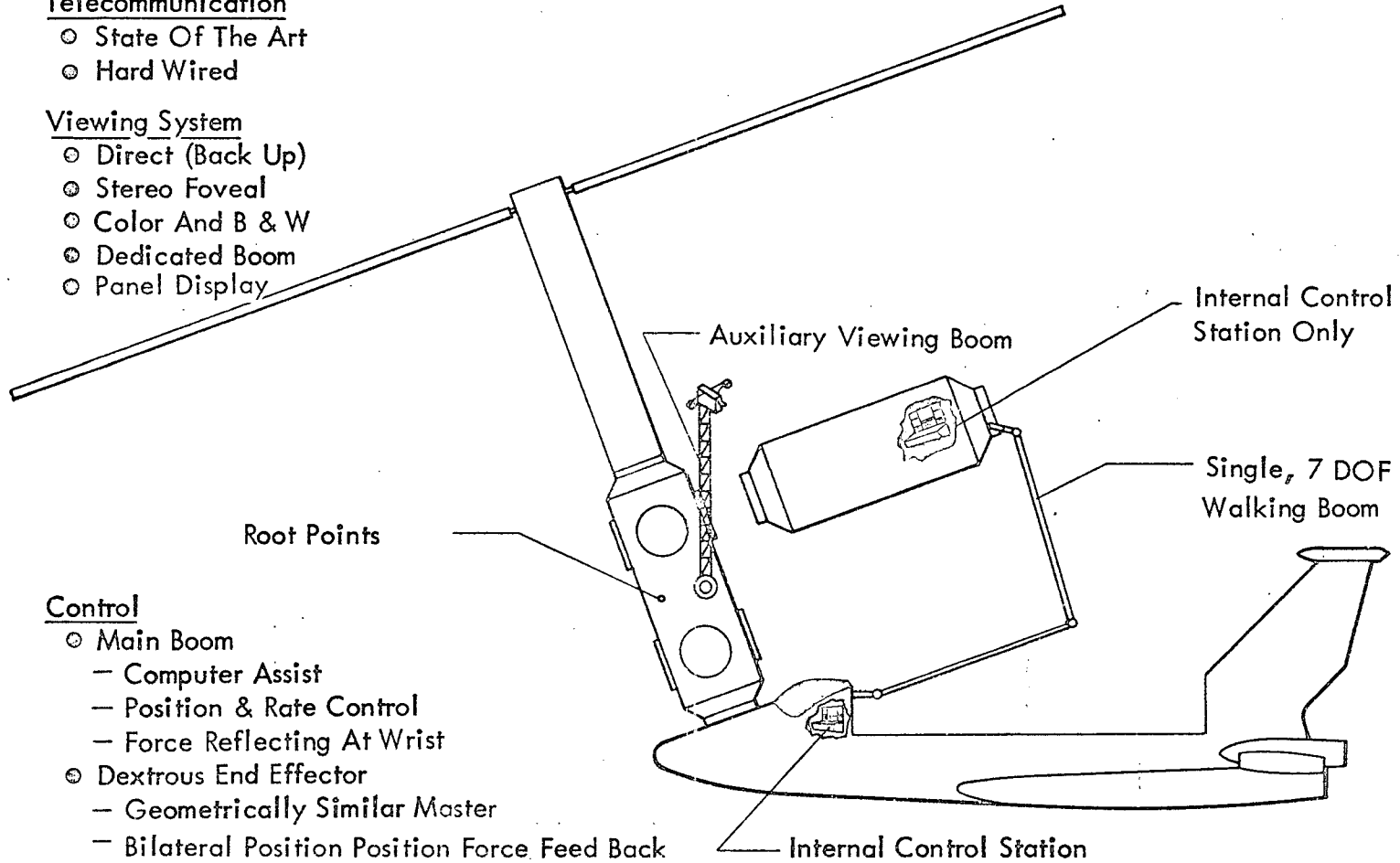
The MSC approved manipulator system concept is illustrated in Figure 3.3-1. Refined requirements for this system and a description of the various parts and subsystems including the rationale for their recommendation and selection are presented in this section.

Telecommunication

- State Of The Art
- Hard Wired

Viewing System

- Direct (Back Up)
- Stereo Foveal
- Color And B & W
- Dedicated Boom
- Panel Display



Control

- Main Boom
 - Computer Assist
 - Position & Rate Control
 - Force Reflecting At Wrist
- Dextrous End Effector
 - Geometrically Similar Master
 - Bilateral Position Position Force Feed Back

FIGURE 3.3-1.
MSC APPROVED MANIPULATOR SYSTEM CONCEPT

3.3.1 Requirements

3.3.1.1 General Requirements

The tasks to be performed by the shuttle/space station manipulator system are: to assemble a modular space station in earth orbit, to perform station repair and maintenance including replacement of propulsion packages, to assist in berthing the shuttle, to unload and load shuttle cargo in orbit and to deploy, service and retrieve satellites from the shuttle.

The basic manipulator system shall consist of an internal control station (one each on the shuttle and station) a single, articulated "walking" main boom, (referred to as the "boom"), and a viewing system (including an auxiliary dedicated viewing boom) capable of presenting the operator with an adequate display or view of the work area. The manipulator system will be configured so that the main and auxiliary booms can be used interchangeably on the shuttle and space station and so that a maximum of commonality between this shuttle and space station can be achieved with other subsystems such as the man-machine interface (controls and displays) and viewing systems. The main and auxiliary booms shall be capable of being stored and transported in the shuttle cargo bay. The boom can be equipped with general purpose, dexterous multiple arm end effectors as well as with specialized end effectors for general and special tasks respectively.

3.3.1.2 Subsystem Requirements

3.3.1.2.1 Boom Requirements

The boom will have a maximum force level determined by the requirement to deploy, manipulate, berth and retrieve shuttle payloads and in addition to assemble, maintain and repair the modular space station. The boom will assist in berthing the shuttle within its force and strength capabilities. In berthing the shuttle, the manipulator shall, upon capture

1.3A

of the shuttle, transmit its boom joint position and rate information to the shuttle such that the shuttle can use its own propulsion/ACS system to bring the shuttle velocities down to levels where the manipulator system can complete the arresting and berthing task.

The boom will be capable of moving from one hard point to another on the shuttle or space station. The hard points shall be capable of providing the required electrical power and control inputs required by the manipulator system.

3.3.1.2.2 Control Module

The requirement for a separate external control module with independent power, environmental control and life support systems is eliminated.

3.3.1.2.3 Control Station

An internal control station will be used on the station and shuttle. The manipulator control station will be a modular addition to the control/crew module for the space station. The possibility of time sharing the space station and shuttle computers for manipulator functions will be investigated.

3.3.1.2.4 Man/Machine Interface

The manipulator will require a minimum of training and prior experience for the operator. There will be no encumbrances to the operator for viewing or operating the manipulator. The manipulator shall be controlled only from the primary control station in the space station or shuttle. There will be no portable control stations.

3.3.1.2.5 Visual System

(1) Viewing Geometry. The system should assure coverage of the entire envelope reached by the teleoperator as well as the regions of space adjacent to the envelope so as to provide information about objects manipulated by the teleoperator. Standby optical instruments, such as a

dual field variable power (zoom) stereoperiscope should be available in case of video system failure.

(2) Illumination Conditions. The system should be capable of functioning under space illumination conditions, i.e., starlight and sunlight illumination, large brightness gradients across the field of view, and should be immune to direct or specularly reflected sunlight. The lighting system should provide lateral lighting for enhancement of small details when performing inspection tasks.

(3) Optical Detection and Imaging. Visual information acquisition capability should incorporate all or the most essential of visual inputs required both for handling tasks and for flaw detection and malfunction or accident investigation, such as:

- a) Brightness and contrast control capability
- b) Camera mobility
- c) Increased resolution (of the order of 1000-1200 lines)
- d) Variable field of view (zoom)
- e) Stereoscopy
- f) Eye acuity matching (foveal techniques)
- g) Automatic focusing and stereo convergence control
- h) Color
- i) Specialized visual probes and alignment aids

(4) Visual Display and Controls. Minimum adaptation of the observer to the interface should be provided. In other words, the ideal situation would be when the operator could not distinguish between direct observation and the use of the viewing system. It is also desirable to reduce the number of constraints. Therefore, to allow free head movement, the display can be head-mounted or at a suitable distance. Head-aiming or

eye-aiming will make the camera pointing control not interfere with the conscious tasks of the observer. Stereoscopy will provide interfacing with binocular vision. A foveal-peripheral mode should be used to optimize resolution. The controls for stereoscopic convergence and focusing should be either automatic or eye-aimed, in order not to interfere with conscious tasks.

(5) Fail-safe Feature. The elements of the viewing system should be either redundant or not affect the functioning of those remaining in case of individual failure of one or more elements. The system should be conceived as a basic unit consisting of a monocular fixed focus, hyperfocal, fixed focal length gimballed video camera, to which the automatic aperture control, focusing, zooming, stereo, foveal, color functions can be added. For example, the zoom and iris system can be conceived as spring-loaded, with automatic return to a fixed focal length, minimum aperture and hyperfocal distance (fixed focus) in case of failure of the controls so that the system could function at a basic level for as long as the video part of the camera is operative.

3.3.1.2.6 Control System

The control system must have a slow and steady response to avoid excess flexing and to facilitate accurate and smooth berthing. The control will be computer assisted for safety and better performance. The main boom control will be rate control and need not be force reflecting except perhaps for capture operations. The dexterous end effector will have a position-position bilateral force feedback controller. There will be no portable control stations.

3.3.1.2.7 Data Processing and Transmission

The data processing and transmission system must process and transmit control signals and instrumentation signals with high reliability and low error rates. The video channels must provide a high signal-to-noise ratio and provide a high resolution view of the work area

at all times since it is the primary viewing system. There must be a minimum impact on the station and shuttle by the telecommunication system. The manipulator telecommunication system must be capable of providing relative motion information to the shuttle while the boom is plugged into the station and the shuttle, preparatory to arresting and berthing the shuttle.

3.3.2 Boom Configuration

There are three (3) fundamental decisions involved in selecting a boom configuration: (1) The number of booms; (2) the degrees of freedom (DOF) for the boom(s) and (3) the kinematic arrangement of the DOF's or joints. Once these decisions are made design of the boom becomes a fairly straightforward engineering problem.

Consideration of the number of booms required is given in Section 3.2.2.1 "Single vs. Multiple Booms" where it is concluded that two or more interactive booms are not practical (or even possible) when the current state-of-the-art in manipulator control and human factors are considered. Furthermore scale model studies of the various operations required on the shuttle and station show that all of the tasks can be accomplished with one main "working boom", although some tasks (such as satellite servicing) will require a special device (such as an auxiliary boom or supporting fixture). However such a device can generally be made lighter, less complex and will be less costly than a second working boom and when it is not required on a mission it need not be carried. Thus only one active boom can be operated at any one time on a given object and since complete space station assembly and shuttle/station cargo handling can be accomplished with only one boom without using any special end effector, it is logical to select a single boom for the basic manipulator system configuration. This choice also makes it possible to use whatever weight allowance there is to make the single main working boom as rigid as possible and obviously much more rigid than each of separate booms if a multiple boom concept were to be used for the same weight allowance.

Six DOF's are required to place a vector (fixed to the tip of the boom) in any arbitrary location in any arbitrary orientation. Scale model studies as described above in conjunction with analyses of past and current manipulator experience (see Section 3.2.2.2) led to the candidate boom configurations shown in Figure 3.2.2-11. Additional model studies showed that the extensible arm configurations are not required even though they may be convenient in some situations. Extensible arms cannot be made as light or simple as a fixed arm for the same bending and torsion load capability thus they were ruled out.

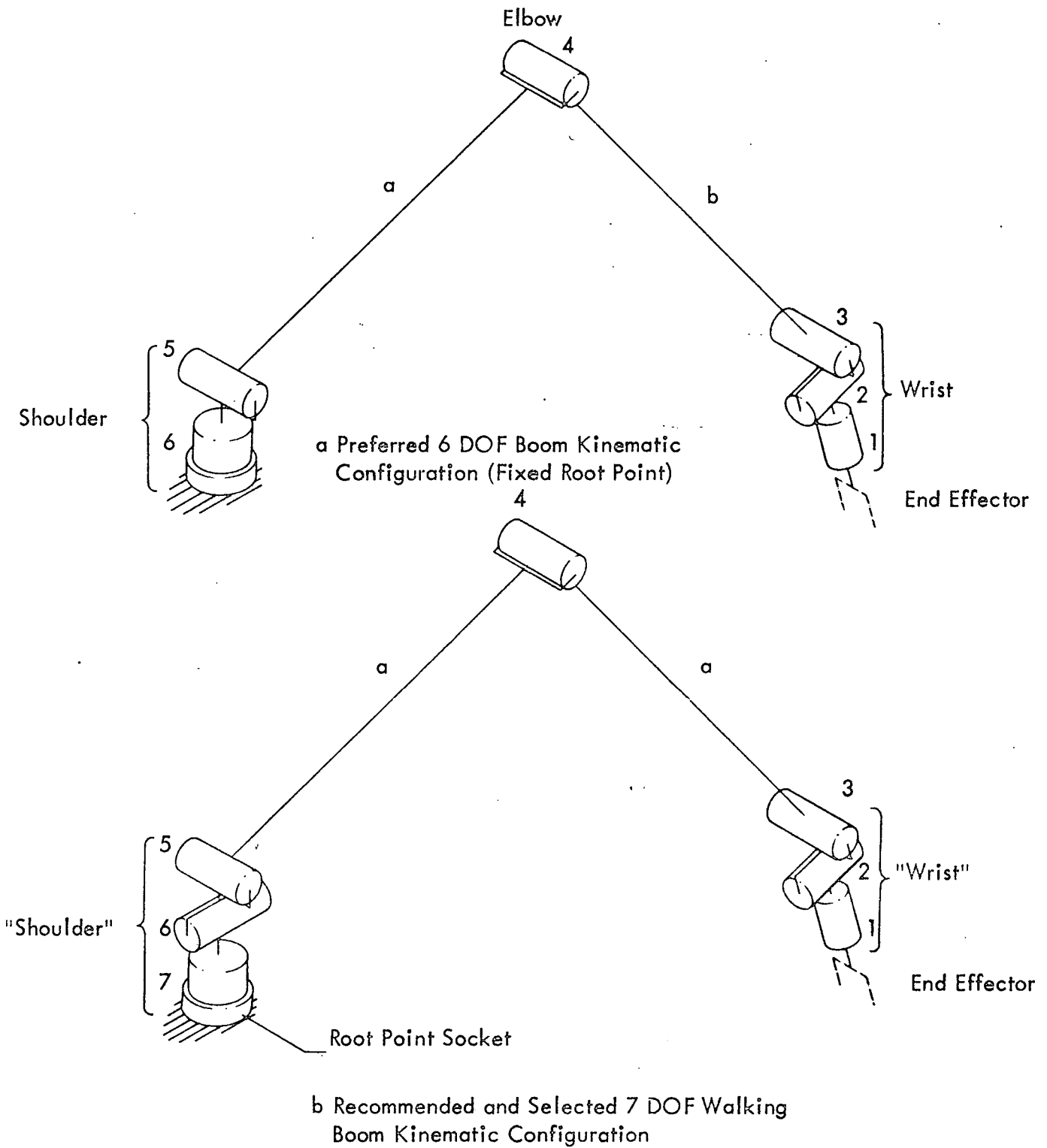
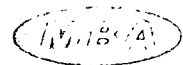


FIGURE 3.3-2.
SELECTED WALKING BOOM KINEMATIC CONFIGURATION



Consideration of the boom mobility requirements (particularly around the space station), operator visual requirements and of the complexities involved when a manned control module is used led to the conclusion that a control station internal to the shuttle or space station should be used. The size required of an external, mobil, manned control module capable of ~5 hours independent operation precluded passing the module between adjacent station side modules unless greater separation is provided than in current design configurations. Unless greater separation is provided, mobility becomes more complicated because the module must always be passed around the ends of the station side or core modules. Furthermore the fact that man is in the module introduces safety problems and requires life support utility connections which would not otherwise exist. The primary reason for considering an external manned module is to provide for direct viewing of the work scene. There are many tasks, including certain phases of station assembly, where direct vision is not adequate or even possible. Thus a video system capable of providing an adequate display of the work scene to enable task accomplishment is required even though direct viewing may be possible for some tasks. Since such a video viewing system is required there appears to be no reason to have a manned external module particularly in light of the other complications that it introduces as described above.

On the basis of eliminating the manned module and on the scale model and other studies noted above, the preferred 6 DOF kinematic configuration shown in Figure 3.3-2(a) was evolved. This configuration complies with all of the design rules presented in Section 3.2.2.2. The shoulder and wrist-joint assemblies would be made as compact as possible (short overall length). The arm lengths (a) and (b) need not be the same length.

The walking boom concept was evolved as a very attractive and practical way of achieving the necessary mobility particularly on the space station but also on the shuttle. The walking boom concept is particularly attractive in terms of interchangeability and general purpose use. The concept consists simply of making the boom symmetrical about the elbow

joint so that it can be operated from either end in identically the same manner and of providing a strategic array of root point sockets which either end can plug into. A seven DOF configuration results as shown in Figure 3.3-2(b). The "extra" joint in the "shoulder" (joint 6 in Figure 3.3-2(b)) can be used as an indexing joint but would normally be inactive (locked) during task operation. The boom "walks" but plugging end over end from one root point into another. Necessary interlocks and safetys are provided to assure that the "new" shoulder point is properly attached before the "old" shoulder is detached. Joints (1) and (7) are designed such that they connect directly into the root points. Thus if root points are built into cargo modules, station modules and other payloads they can be handled without any special end effector on the boom.

Preliminary layouts of the boom indicate that each side of the elbow will be 9.1 m (30 feet) long. The distance from the wrist to the elbow will be 7.3 m (24 feet) and from the wrist to the root point will be 1.8 m (6 feet). The end connector of the boom, the part that plugs into the root point will be a male type plug-in collet, cam actuated so that it will hold the boom rigidly in place. It will also be configured to provide electrical contact for all the power, control, monitoring and video circuits. The boom structural material will be a light weight alloy of aluminum titanium or beryllium.

3.3.3 Actuators

As indicated in Section 3.2.3 "Actuators", selection of the boom actuators was not considered important to the selection of the overall boom concept. That is, whatever boom concept is selected, actuators can be devised as required. This assumes that the selected boom configuration will not be so unusual that it doesn't lend itself to normal actuator design practice. There is no problem in this respect as can be seen from Section 3.3.2 above. Actuator analyses and selection is presented in Volume III, Part I, Section 6.3.5, "Actuator Configuration".

3.3.4 Man/Machine Interface

The scale factor between the main boom and man (20/1), the small force levels involved [≤ 45.4 Kgs (≤ 100 lbs)], the relative flexibility of the boom [≤ 30 cm (12")] and the large masses involved [up to $\sim 130,000$ Kgs ($\sim 285,000$)] require that a computer interface between man and the boom (see Sections 3.2.2.1 "Single vs Multiple Booms" and Section 3.2.5.1 "Task Analysis"). For time consuming, slow translation type movements, it is desirable to have the computer control the boom in a supervisory mode. For such tasks, no force reflection or operator "feel" is required. The computer can assure that force limits are not exceeded. For other precise tasks, such as capture of a fly-by object (the shuttle for example) or such as dexterous manipulation with an anthropomorphic end effector (repair work), force reflection is required. The requirement for a computer makes new master/slave control concepts possible; that is, it is not necessary to have true geometric sensitivity between master and slave if the computer is used to provide the necessary coordinate transformations to make the master/slave end points move and orient as if there was true geometric similarity.

Several acceptable man-machine interfaces can be postulated and without simulation and human factor studies it is difficult to define what might be considered a truly optimum configuration. The selected man-machine interface described below is the result of screening about 25 different approaches. It is compatible with the control and viewing requirements established for the overall manipulator system and does represent a baseline from which a new optimum configuration can be defined. The selected concept allocates control functions between man and machine in a logical manner, and incorporates several of the control techniques now being developed for advanced remote manipulation in other applications. Transformation of the operational concept to a physical interface (the control console) is treated in Volume III "Concept Analysis".

3.3.4.1 System Concept

Figure 3.3-3 illustrates schematically the (selected man-machine interface system concept). The operator interfaces with a primary set of displays and controls at the control console. An on-board computer intervenes between the man/machine interface and the controlled system. The type and degree of intervention is a function of the system task. The controlled system itself consists of the main boom and its permanent end-cluster, a set of "plug-in" end-effectors, and the modules, cargo, or other objects to which the end connector or end-effectors may be attached.

In the following sections, this concept is elucidated for the primary control modes.

3.3.4.2 Translation Control

Figure 3.3-4 illustrates the primary control and feedback paths. Primary control of the boom in translation is by the computer through indexing and supervisory routines. Movements of the end-effector are planned and requested by digital means, using previously established indexing coordinates, or by means of a small analog model of the manipulator.

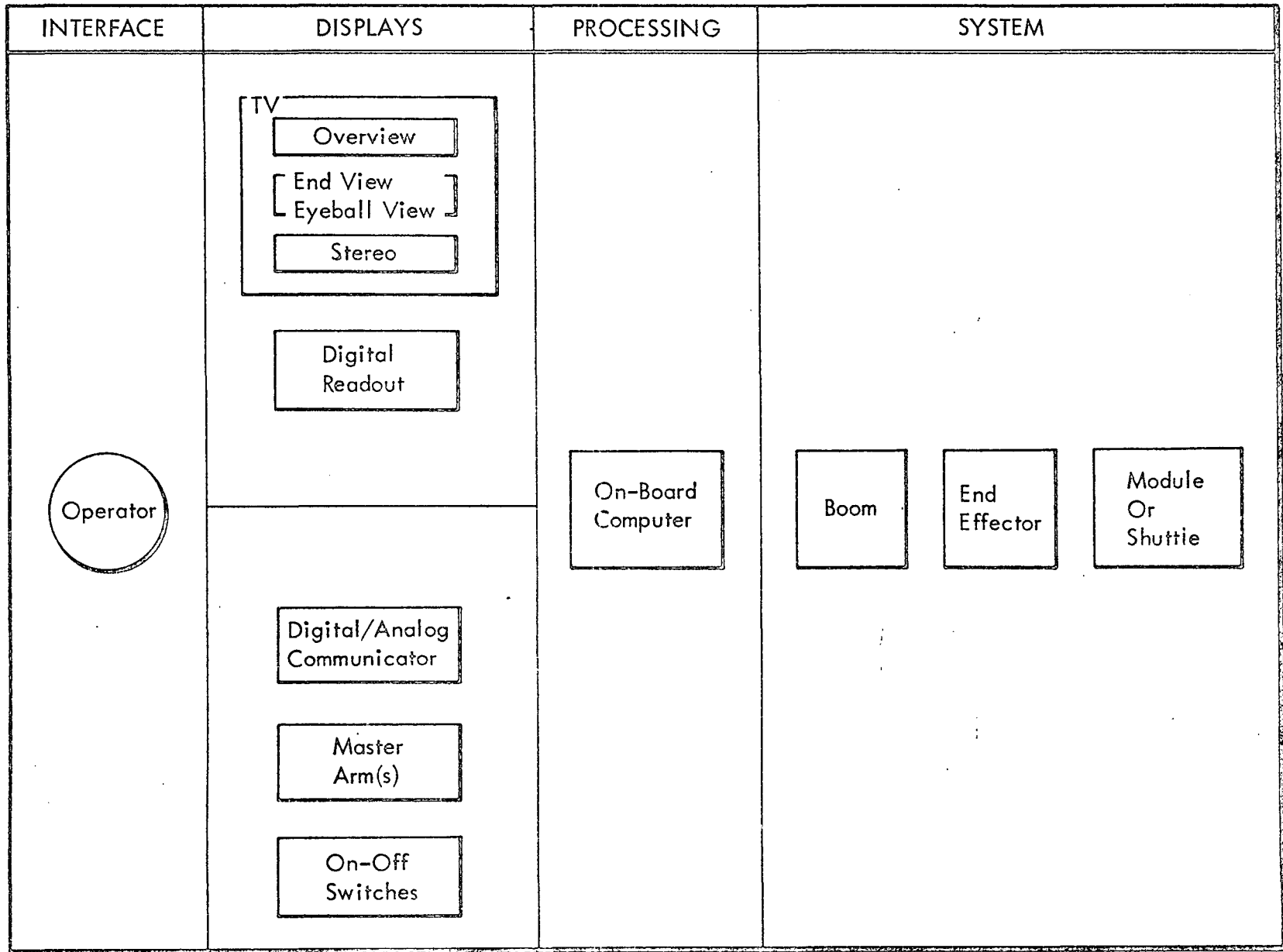
Operations in progress are monitored through available overview cameras (on the camera boom and at the distal and proximal ends of the main boom) and through digital readouts generated by the computer and by direct observation.

Computer translation brings the end-effector or load to within a few feet of its intended location on the station.

3.3.4.3 Mating and Docking Control

Figure 3.3-5 illustrates the primary control and feedback paths.

The operator translates and orients the loaded or unloaded end-effector by means of a "quasi-isometric" joystick controller (a slight amount of movement may optimize control "feel"). The joystick is provided by fixing the dexterous master arm in a convenient position. The required six degrees of freedom are contained in a single right-hand unit. If interaction prevents this, the three degrees of freedom for translation are controlled by the left-



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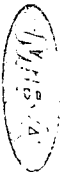


FIGURE 3.3-3.
OPERATIONAL CORE OF SELECTED MAN-MACHINE
INTERFACE DESIGN CONCEPT

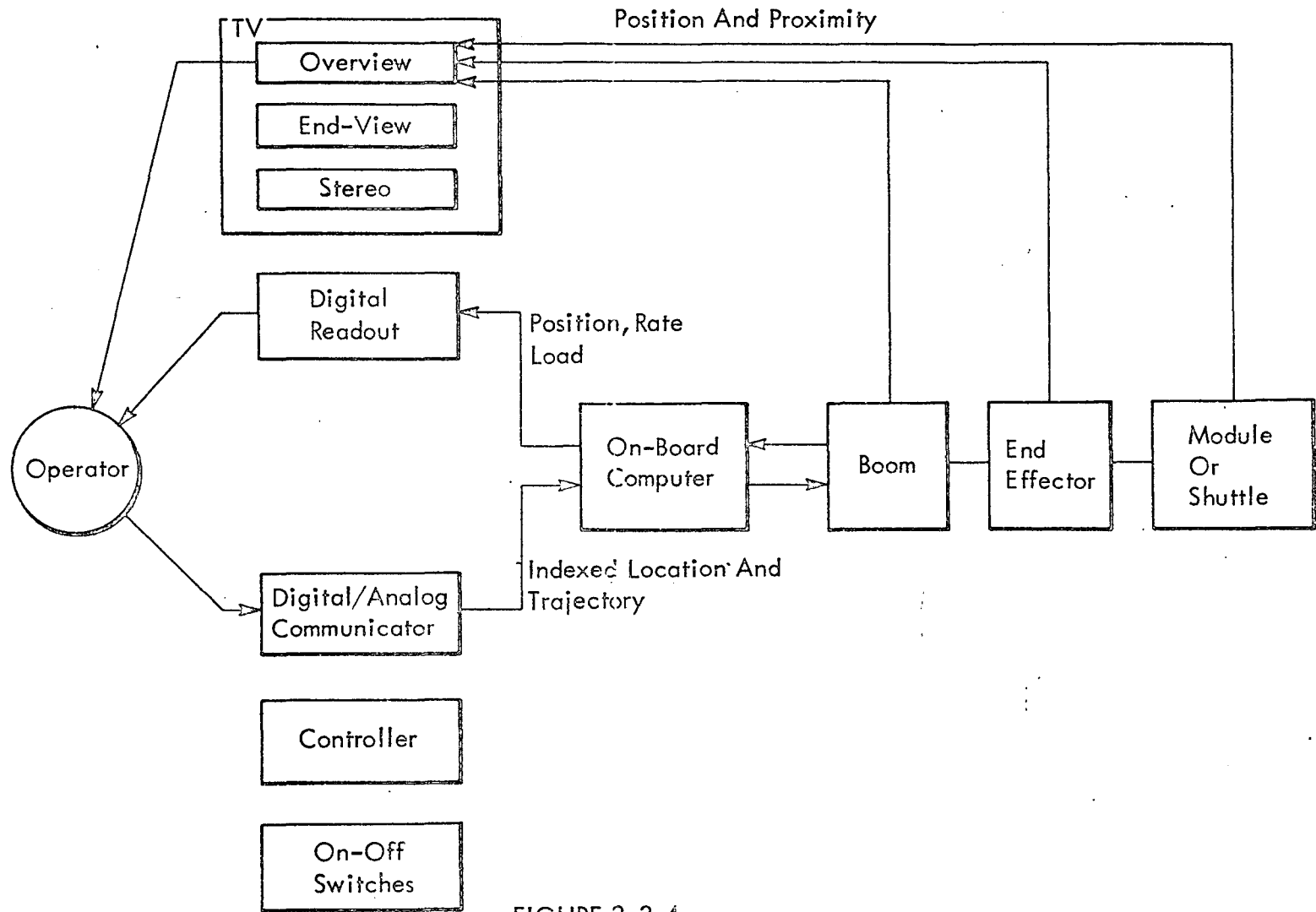


FIGURE 3.3-4. TRANSLATION CONTROL MODE



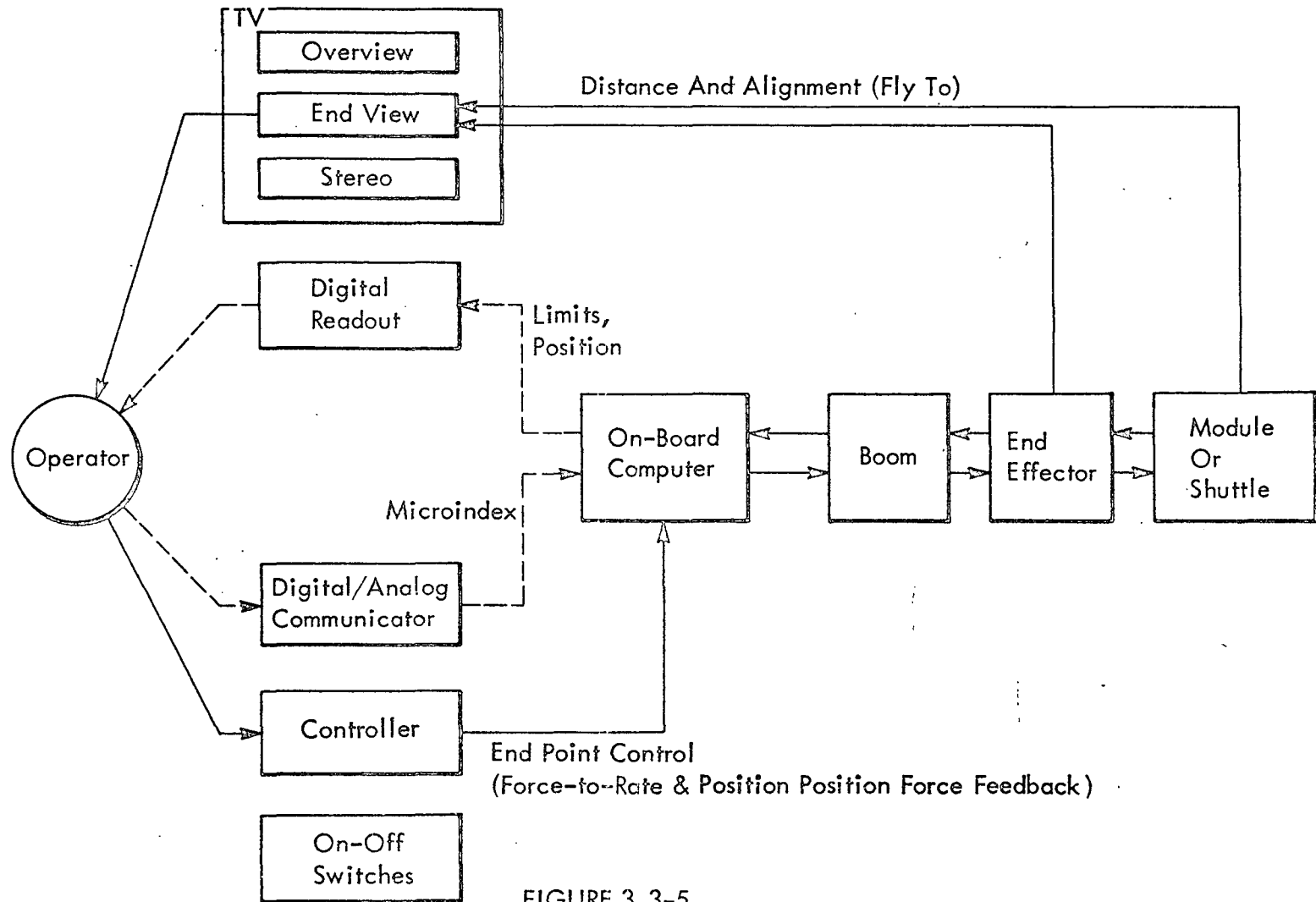


FIGURE 3.3-5. MATING AND BERTHING CONTROL MODES

hand unit, and the three degrees of freedom for orientation by the right-hand unit (a corresponding left-hand unit is required for special end effectors including dexterous arms). Force or torque at the controller produces a proportional rate of movement at the end effector.

Mating and docking is monitored by a TV camera mounted distal of the end cluster, so that the operator actually "flies" the effector or load into its designated location. Alignment guides similar to those used in previous space docking operations are provided. In addition, camera orientation on the boom may be changed between effector mating and module docking operations to compensate for differing directions or approach. Direct visual observation augments the TV display wherever possible.

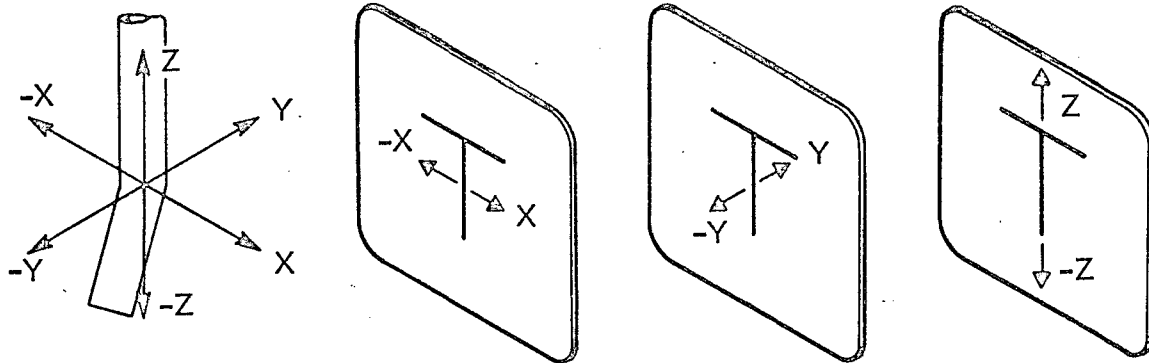
Computer-assisted end point control is used to provide compatibility between how the operator pushes on his stick, and how the end point translates on the display. That is, left-right, in-out, and up-down forces on the stick always produce similar movements of the alignment guide relative to the target object on the display screen. This concept is illustrated in Figure 3.3-6(a). A "T" type alignment guide is shown, other types are also feasible.

Since the display camera is mounted distal of the boom end-cluster, orienting movements are automatically equated on the display screen for any boom position. The suggested correspondence of stick torques to display movement is presented pictorially in Figure 3.3-6(b).

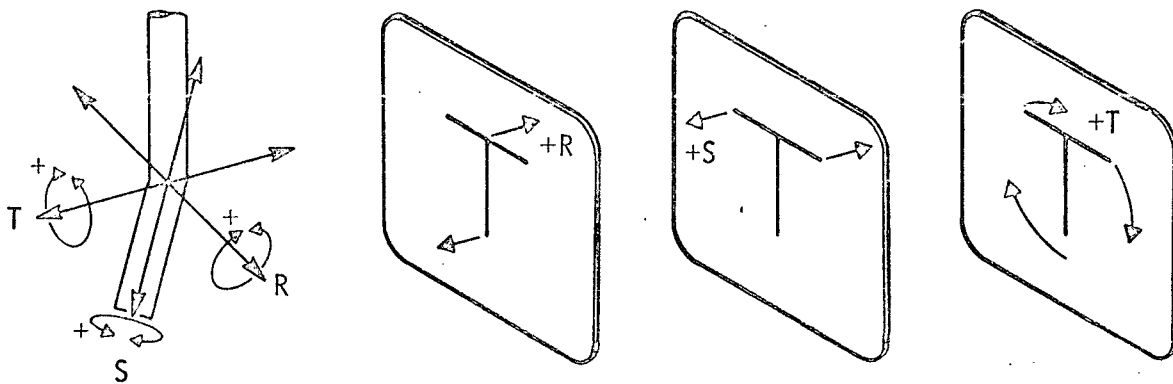
An auxiliary control mode is "micro indexing" through supervisory computer control. This gives the operator capability to "step" the end-effector by small fixed displacements in any direction. This control path is shown dotted in Figure 3.3-5.

3.3.4.4 Dexterous Control

Figure 3.3-7 illustrates the primary control and feedback paths. Control of the dexterous end-effectors is by the same end-point technique used to control the main boom. In this case, the operator uses the stick controller to maneuver the claw or tool into contact with the work along "anthropometric" coordinates such as "reach", "raise", "lower", etc.



Control/Display Relationships in Translation



Control/Display Relations in Orientation

FIGURE 3.3-6.
CONTROL/DISPLAY RELATIONS DURING
MATING AND BERTHING OPERATIONS

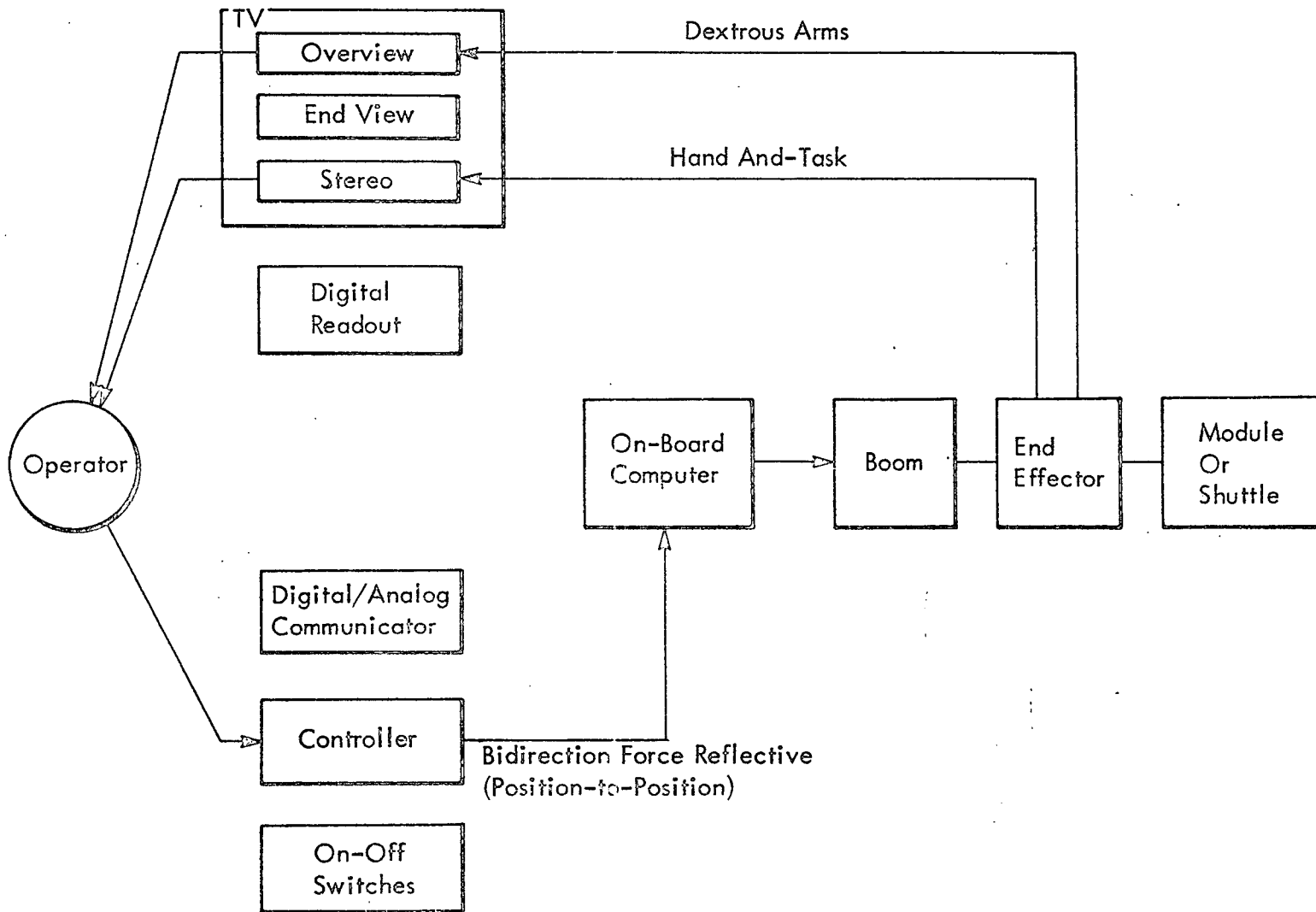


FIGURE 3.3-7.
DEXTRIOUS CONTROL MODE

The operator monitors the work of the slave arms through a stereo/foveal TV system. This gives him a 3-dimensional image of the immediate work space, with higher resolution in the central position than in the periphery. He may also utilize an overview camera to show the general position of the dextrous effector relative to the workspace or adjacent structures.

3.3.4.5 Emergency Control

Figure 3.3-8 illustrates the control and feedback path.

It is assumed the computer is disabled. The operator controls the boom directly through switches which run the individual joint actuators at fixed rates in either direction.

Position of the boom, end-effector, and load is monitored by means of all available TV cameras, and also by means of joint-angle sensors on the boom. Operation is slow and stepwise.

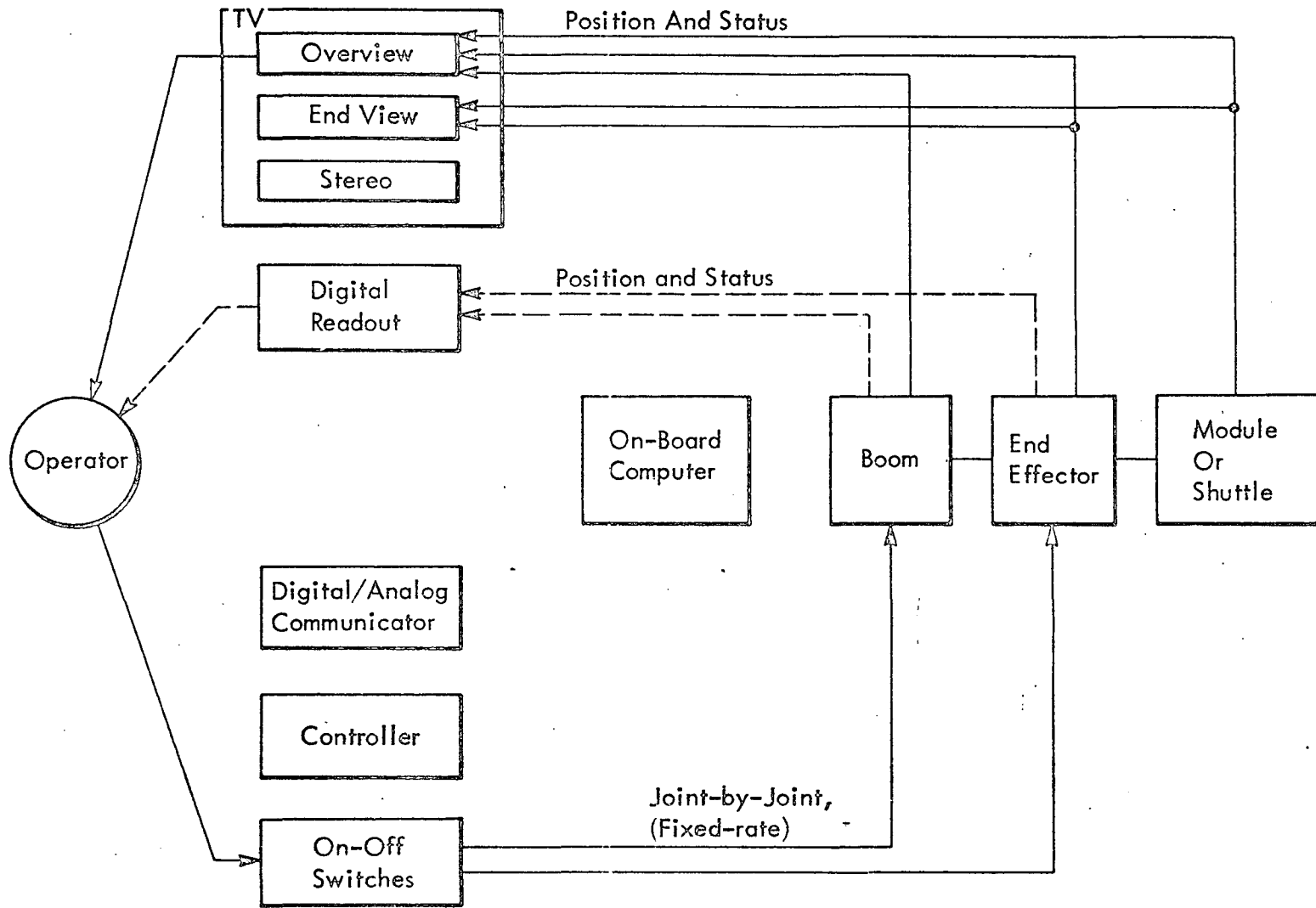


FIGURE 3.3-8.
EMERGENCY BACKUP CONTROL MODE

3.3.5 Visual System

As described in Section 3.2.6 "Visual System", the technology and component availability for the visual system is very good. The type of visual system required is very task dependent; that is, if dexterous, precise tasks are involved stereoscopic, high resolution viewing is required; if on the other hand only space station assembly, cargo module transfer or simple satellite deployment are involved, monocular, single field, moderate resolution viewing may be adequate. In the present effort, the full spectrum of tasks are involved, therefore a stereoscopic, high resolution black and white and color system has been selected.

Conservation of video bandwidth is important and therefore a two-field, high resolution (1200 line) foveal/low resolution (1200 line over ~ 4 times the foveal area) peripheral system has been selected. The resolution of such a display provides a 2-step match of the natural eye acuity angular distribution. (See Figures 3.2.6-1 and 3.2.6-3).

In order for the video cameras to be able to cover the entire functional envelope of the manipulator, multiple locations will be used, such as, "head" of the dexterous manipulator, shoulder and wrist of the boom, critical locations such as on visual alignment aids and on a dedicated boom described below. All cameras will be mounted on remotely controlled pan and tilt orientable supports. The cameras on the dexterous manipulator and the main boom wrist and shoulder will be stereo-foveal, on the dedicated boom will be foveal only and the other cameras will be single field. The cameras will use image tubes with silicon matrix, safe against direct sun illumination. Other camera features will be automatic brightness control, automatic focus and color wheel (to be used only when color is required). Special purpose attachments, such as endoscopes can also be provided. The rationale for, and greater detail on, these features are given in Section 3.2.6.

The initial recommended concept for primary video display and camera position control was to use a mobil viewer as described in Section 3.2.6.11 and as shown in Figures 3.2.6-5 and 3.2.6-6. However, on further consideration by NASA MSC personnel, it was believed that even though such an

approach could provide a high quality optical display and a simple, natural camera position control mode, the possible cumbrance to the operator made it less desirable than a fixed panel mounted display. Accordingly, a panel mounted concept as shown in Figure 3.2.6-4 was selected and approved. Camera position control for this display concept can be accomplished by eye direction tracking techniques, such as are under development at Honeywell, at the Transportation Systems Center of the U.S. Department of Transportation and at Stanford Research Institute.

As described in Section 3.2.6.1, the selected image tubes have the dynamic range to accommodate low illumination levels up to direct sun light illumination, although they cannot resolve such levels simultaneously. Illumination in earth shadow therefore presents no serious problem and can be accomplished with dual beam incandescent lamps. It is believed that the high brightness gradients in the sunlight condition can be accommodated by field sharing and camera positioning as described in Section 3.2.6.12.

In order to obtain adequate viewing of the many possible work areas, it was concluded that a separate dedicated auxiliary viewing boom is required. With such a boom, a high resolution (monocular) foveal camera can be focused at any arbitrary work area at any desired attitude (within the reach envelope of the viewing boom). The viewing boom would be configured to mate with the main boom root points so that it can be placed at a variety of locations about the station or shuttle.

Since there are no large dynamic or active loads on the viewing boom [it need only support the cameras and lights which together weigh about 23 Kg (~50 lbs)] the viewing boom can be of light weight construction compared to the main boom. The astromast type booms under development for solar panel deployment are well suited for the viewing boom (see Figures 3.3-9, -10, and -11). By mounting such a boom on a 2 DOF shoulder attachment, the extensible feature provides the third DOF required to locate the distal end of any desired location within the reach envelope of the boom. By attaching a 3 DOF orientor assembly on the tip, the camera/light assembly can then be placed in any desired orientation at any given location of the tip. Therefore, an astromast type, dedicated viewing boom has been selected for the basic mani-

pulator system. It should be noted that although its force capability is low compared with the main boom (by a factor of say ~ 5), the auxiliary boom could still be used as a back-up emergency boom for some operations.

The astroboom mast illustrated in Figures 3.3-9, -10, and -11 has an envelop diameter of 20"; however, smaller versions (diameter ≈ 10 ") have been developed. In either case the booms collapse into a very compact volume having a length on the order of .76m (2-1/2') to 1.52m (5'). The collapsed astromast should present no stowage problems on either the shuttle or station.

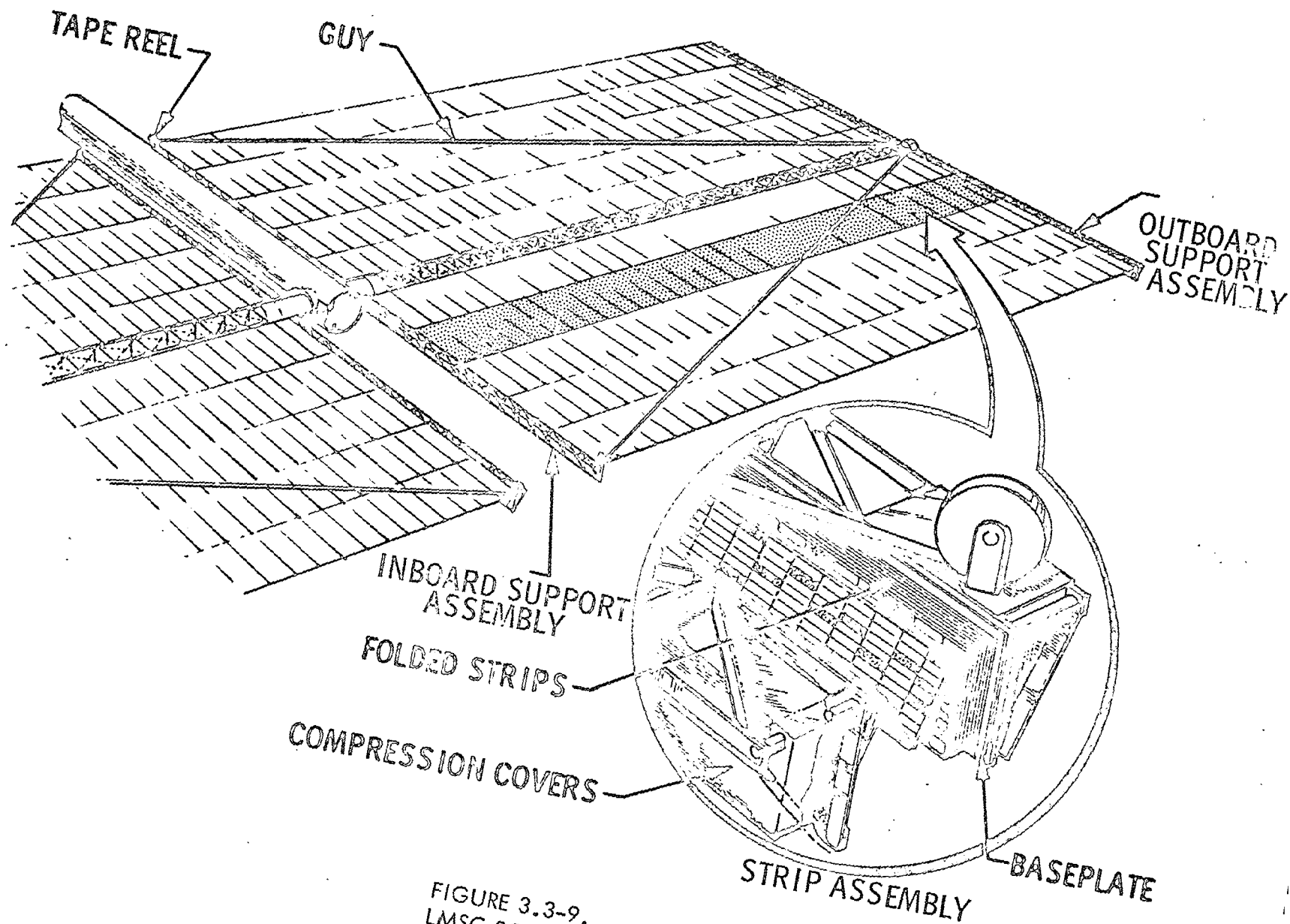


FIGURE 3.3-9.
LMSC SOLAR ARRAY WING

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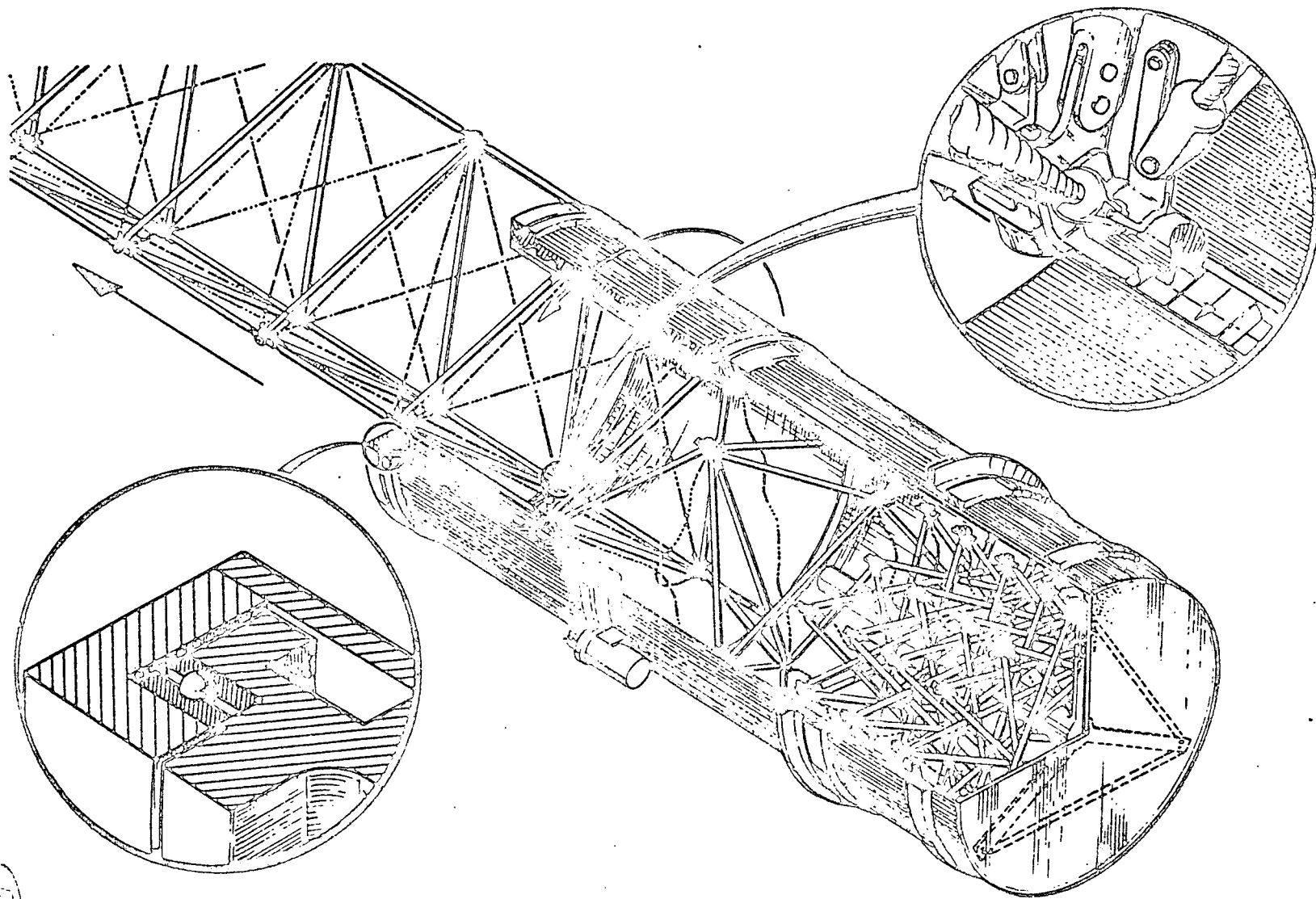


FIGURE 3.3-10.
EXISTING LMSC ASTROMAST CUTAWAY
DETAILS AVAILABLE IN TECHNOLOGY EVALUATION
REPORT LMSC-A981486



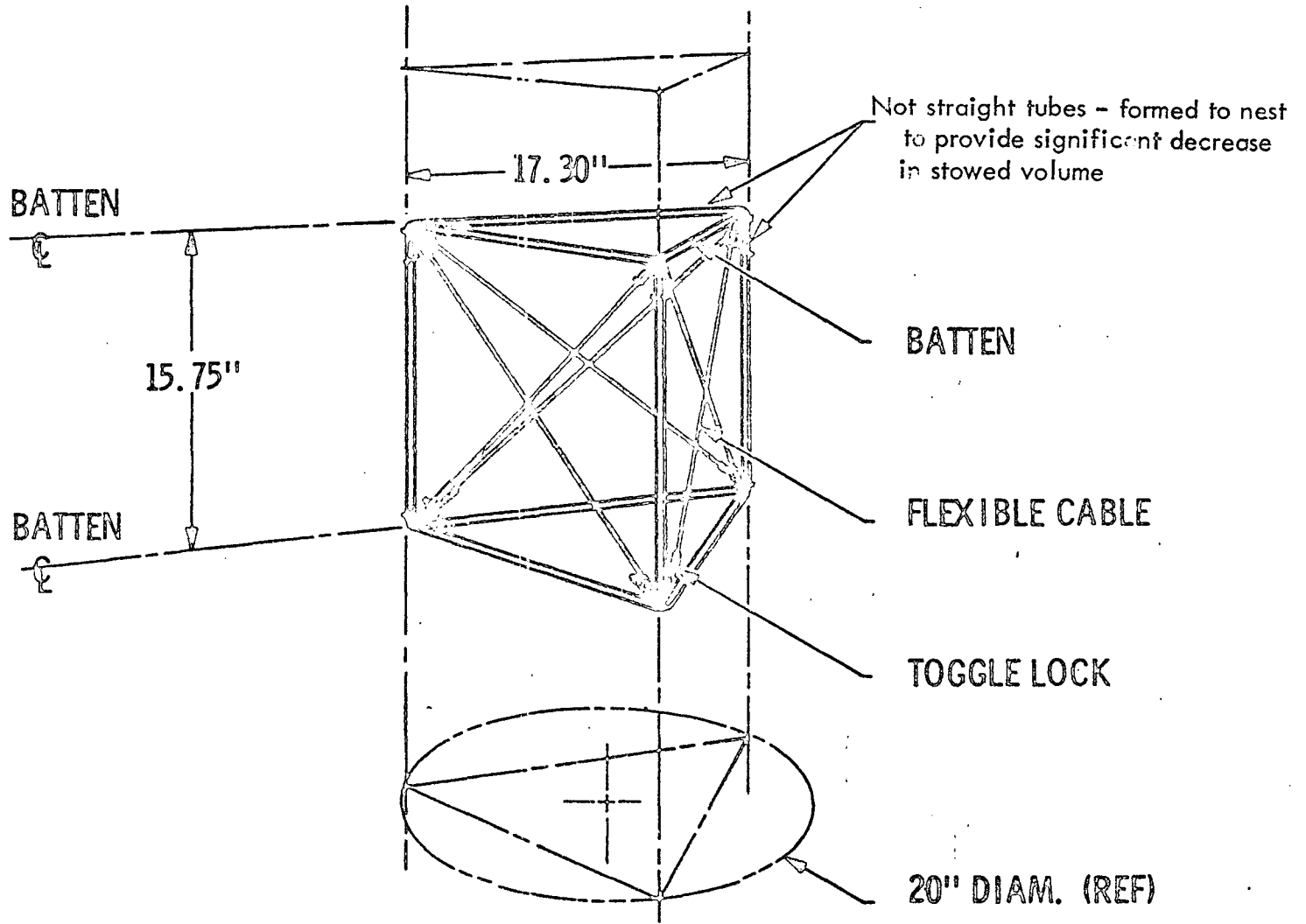
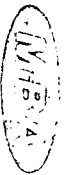


FIGURE 3.3-11.
EXISTING LMSC ASTROMAST BAY DETAIL



3.3.6 Data Processing and Transmission System

The data processing equipment required for the manipulator system is state-of-the-art and almost available on an "off-the-shelf" basis. Therefore, no attempt has been made to define the processing equipment for concept selection. However, the overall processing and transmission concepts have been considered and the following approaches selected.

Hard wire as opposed to RF radiation is best choice for video control and monitor signal transmission because of the ghosting, fading and multipath problems that will occur in working around the space station and shuttle. The space station is of particular concern with regard to RF electromagnetic radiation transmission because of the many configuration changes that it can be expected to evolve through (i. e., beginning as a minimal size and growing to a large multimodule station with frequent module exchanges for cargo transfer, etc). It appears impractical to attempt building the directional, high gain antennas that would be required for satisfactory signal transmission for all boom and station/shuttle configurations. This is particularly so when it also appears that a hard wire RF transmission system is straight forward to achieve.

Of the several video hard wire transmission systems described in Section 3.2.8.2, the parallel coax has been selected as the best choice since it offers low loss, low reflection performance and can provide a high bandwidth capability. Furthermore, a parallel coax system is light weight (a few Kgs) and is compatible with the space station since parallel coax is planned for it also. Similarly there should be no compatibility problems on the shuttle.

A parallel pulse code modulation (PCM) system has been selected for command and monitor signal transmission. The selection rationale is presented in more detail in Section 3.2.8.1. In summary, a parallel PCM system was selected over either an analog or serial pulse code modulation system because it offers the best overall in terms of reliability (more reliable than an RF system), low weight (lower than an analog system), low cost (lower than a serial PCM system), high accuracy (higher than analog), growth capability (better than analog), and compatibility with the space station and shuttle (it is known that the station will use a parallel PCM system).

3.3.7 Materials

Although no weight limit was set for the concept selection phase, it is clear that low weight is desirable. Thus low density materials should be used where possible and practical. The boom/actuator assembly is of particular concern since it is the single heaviest component and it must be made as stiff as possible. Filament wound and other composite materials offer potential advantages, but require significant state-of-the-art development. Therefore a ground rule has been established (see introduction to Section 3.3 "Concept Selection") that the primary structural materials will be limited to alloys of such light weight metals as aluminum, titanium or beryllium (see also Section 3.10 "Materials").

Greases, oils, and lubricants in general, should be the type that will not outgas, for outgassing on mirrors, space telescopes, etc. could ruin the mission of these instruments. The state-of-the-art for space lubricants is well advanced so that no difficulties should be encountered in this area.

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The state-of-the-art of manipulator and teleoperator technology was reviewed and updated during the course of this study. Documentation of the state-of-the-art is represented by the bibliography presented in this section. This bibliography also includes some standard works used as reference material in certain parts of the study. The bibliography is organized in the following manner.

- I General Teleoperator Technology
- II Teleoperator Space Applications
- III Manipulator Technology
- IV Control Technology
- V Display Technology
- VI Viewing Systems
- VII Environmental Control and Life Support Systems
- VIII Power Systems
- IX Materials

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VII - INFORMATION PROVIDED BY
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ENVIRONMENTAL CONTROL SYSTEMS (ECS)
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- EC/LSS - 1. Lunar Module Environmental Control Subsystem
Explains the basic function and operation of the LM Environmental Control Subsystem (ECS) and lists the salient parameters of the subsystem components.
- EC/LSS - 2. Apollo Portable Life Support System
Explains the basic function and operation and lists the salient components parameters for the following Second Generation Apollo Portable Life Support Elements
- a) Portable Life Support System (PLSS)
 - b) Oxygen Purge System (OPS)
 - c) Buddy Secondary Life Support System (BSLSS)
 - d) Pressure Control Valve (PCV)
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APPENDICIES

- A) STATEMENT OF WORK
- B) SPACE STATION AND SHUTTLE PARAMETERS



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ENGINEERING AND DEVELOPMENT DIRECTORATE

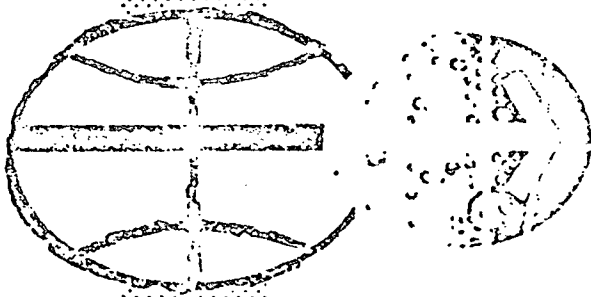
STATEMENT OF WORK

FOR

PRELIMINARY DESIGN OF A

SPACE STATION ASSEMBLY AND

CARGO HANDLING SYSTEM



MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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1.0 PURPOSE

1.1 OBJECTIVE

The objective of this study is the engineering analysis and development of the preliminary design of a system for assembling a Shuttle Launched Space Station and loading or unloading Shuttle cargo.

1.2 END PRODUCT

The end product of the contractual effort is to be drawings of a full-scale mockup and a report which describes the preliminary design of the device and its capabilities.

1.3 BACKGROUND

A Teleoperator (T/O) is a general purpose, dexterous, cybernetic machine which has man in the control loop. T/O's have been employed to make it possible for man to efficiently function in hostile environments on earth and under the seas. This effort shall investigate the application of a device employing T/O principles to accomplish specific tasks in the hostile environment of outer space.

It is reasonable to assume then that no basic research is required before a T/O can be developed for space application. This SOW is based upon this assumption and seeks to focus the available technology upon the specific application of developing a device for assembly of a space station utilizing T/O techniques.

2.0 SCOPE

2.1 GENERAL

The contractor will provide the necessary resources to perform engineering analysis and preliminary design of the assembly and cargo handling concept described in Section 3.0 of this SOW.

2.2 PROGRAM SCHEDULE

The contractor will support the contract effort and comply with the program schedule depicted in Figure 1.

3.0 TECHNICAL REQUIREMENTS

3.1 GENERAL

3.1.1 STUDY REQUIREMENTS

The contractor will be required to develop alternative T/O approaches or concepts that are applicable to the fulfillment of the technical objectives set forth in this SOW. These alternatives will be the result of concept and feasibility investigations, trade-off analysis, engineering assessments and/or other specific identified investigations. Each alternative will: (a) specify any evolving scientific and technological findings and requirements, (b) identify the impact/feasibility of product utilization, and (c) identify the impact that these requirements may have on gross schedules and costs. Based on the alternatives that have been presented, the contractor will be required to rank these alternatives in order of their desirability.

3.1.2 DESIGN REQUIREMENTS

The contractor will prepare requirements which will define in more detail the concepts and theories emanating from the study effort. Environmental conditions under which this equipment is to operate and the performance and the detailed characteristics of the equipment will be clearly specified. Concepts will be definitized to the point where preliminary designs can be prepared.

3.1.3 DEVELOPMENT REQUIREMENTS

These requirements will specify those special factors that must be considered in translating the design data into tangible end items. Specific emphasis will be directed to development requirements in support of breadboarding, prototype fabrication, component testing, empirical testing, and other development criteria that are intended to expose design deficiencies before they reach the manufacturing or operational phase of the project. The contractor may conduct laboratory evaluations to investigate particular design problems.

3.2 SYSTEM REQUIREMENTS

3.2.1 GENERAL REQUIREMENTS

One of the more promising techniques for establishing a space station in earth orbit involves the assembly of modules delivered to orbit by the space shuttle. This technique would also be applicable to the orbital assembly of other advanced systems such as large earth or earth synchronous, lunar, or planetary payloads where modular assembly is required. Fundamental to the concept of modular space station assembly is a technique for transferring the modules from the shuttle to a docking position on the station core element. An analysis and evaluation will be made on a T/O for transferring and maneuvering modules between a space shuttle and a modular space station. The T/O device shall consist of a manipulator boom articulated at shoulder, elbow, and wrist-type joints to accomplish the assembly of a modular space station and unloading and loading shuttle cargo. The contractor shall define the criteria and overall requirements of the device. The device should be designed to permit docking a module to a space station or other orbital module with very low closure rates and with very precise control so that the docking loads are small enough to be absorbed by the device, thereby relieving the requirement for attenuating large docking loads. The baseline T/O will be space station attached and will consist of a manned module which can dock on any of the station's docking ports and which possesses one or more manipulator booms. The space station modules considered will be shuttle launched. The basic T/O functions will be the docking and assembly of the modules onto a station core, cargo docking or cargo transfer to the completed station. A module of this basic type was postulated in the Pre-Phase A Study of a Shuttle-Launched Space Station developed by MSC and now under study by NAR. Attachment 2 contains sketches of the concept.

The T/O module would be smaller than the station modules so that the arms can be stowed externally and still fit in the shuttle bay. The module will have ECS and power systems capable of limited independent operation but intended to be normally connected to the station. A pair of arms (or single arm if determined feasible) will be long and equipped with specialized end effectors. These arms will be used for module docking, cargo transfer, and to move the T/O module between docking ports. A second set of shorter, general-purpose arms will be studied for assembly and other operations. The type and number of end effectors and/or tools necessary to accomplish the assigned tasks are to be determined. Visual systems will be incorporated where necessary, and their utilization evaluated.

Mass characteristics of the modules presently being considered for assembly into a modular space station are listed in Attachment 3.

3.2.2 SUBSYSTEM REQUIREMENTS

The contractor shall define the requirements for each of the subsystems such as: video, instrumentation, power, control, manipulator, and crew operations and man/machine interface.

3.3 CONCEPT EVALUATION

3.3.1 TECHNOLOGY

The capability of current technology to support development of this T/O device shall be investigated and any critical technology development required especially any pacing technology must be identified.

3.3.2 KINEMATICS

The approximate sizes, strengths, and degrees of articulation shall be determined.

3.3.3 INITIAL ANALYSIS

A simple mathematical analysis of a basic dynamic model will be prepared to determine the forces and motions of the arms. The basic strength requirements will be extrapolated from the analytical data.

3.3.4 TELECOMMUNICATIONS

The major subsystem, Telecommunications, shall be designed to the extent necessary to evaluate this subsystem's impact upon system concepts and eventually to integrate the telecommunications design into the selected system. Detailed circuit designs are not required under the assumption that sizing tolerances are not critical.

Trade studies and design effort are to be conducted which result in a conceptual approach and subsystem design which shall be documented to the following extent as a minimum:

- a. Conceptual approach, description and basis therefor.
- b. Block diagram(s).
- c. Parametric description of each element including weight, power, geometry, location, functional performance.
- d. Interface descriptions and requirements on other subsystems.

3.3.5 PRELIMINARY DESIGN

A preliminary design of the various concepts will be established. This will be a very shallow analysis that provides enough information to evaluate the different concepts.

3.4 CONCEPT ANALYSIS

3.4.1 DETAIL REQUIREMENTS

Based upon the results of the preliminary analyses described in paragraph 3.3, the requirements for the systems shall be expanded and developed further to support the detail analysis of a selected concept or concepts.

3.4.2 DETAIL ANALYSIS

The selected concept(s) shall be analyzed in further detail, and the capability of the device to meet the design criteria and requirements shall be established.

- a. The method of controlling the articulation of the booms shall be specified. Any control augmentation required, such as limit switches, shall be considered.
- b. The contractor shall perform an analysis to determine the maximum loads to which the booms may be subjected. A preliminary evaluation of the structural integrity of the arms shall be conducted.
- c. Further dynamic analyses will be performed to determine the power required to actuate the device. Preliminary evaluations of the response characteristics of the device shall be determined.
- d. Study and design effort of the Telecommunications subsystem shall consider as a minimum the following:
 - (1) Hardline versus R.F. transmission.
 - (2) Total signal requirements such as number of signals, signal characteristics, signal requirements versus operational time line, signal accuracies and allowable error rates.
 - (3) Signal formats.
 - (4) Transmission range.
 - (5) Tracking/ranging requirements.

- (6) Local signals versus remote, local computation.
 - (7) Multiplexing techniques.
 - (8) Bandwidth compression.
 - (9) Near field effects, antenna pattern obscuration, signal overloading, electromagnetic compatibility.
 - (10) Television light levels, lighting geometry, automatic light level compensation and protection.
 - (11) Television picture quality aspects such as field of view, depth of field, resolution, contrast range, grey shades, signal/noise, motion rendition, geometry distortion, controlled functions such as lens settings.
 - (12) Television display and control aspects such as scan conversion, head/eye aimed television cameras, human factors considerations such as monitor size.
- e. The types of end effectors shall be investigated to the extent that they affect the design of the booms.

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3.4.3 REQUIREMENTS ANALYSIS

An analysis of the capability of the system to meet the criteria and requirements called for in paragraph 3.2, as expanded by paragraph 3.4.1, will be accomplished.

3.4.4 UTILITY

An analysis will be conducted to determine the extent and limitations of the device's operational utility.

3.5 DESIGN PARAMETERS

The results of the concept analysis shall include in addition to a preliminary design of the selected concept:

- a. Design sensitivity curves with respect to input data.
- b. Estimates of weight and volume.
- c. Estimates of response capability.
- d. Upgrading possibilities.

- e. Future problems.
- f. Estimates of development time and cost.

3.6 MOCKUP DRAWINGS

The contractor shall prepare drawings of a full-scale soft mockup of the system.

3.7 PRELIMINARY DESIGN DRAWINGS

The contractor shall prepare drawings of the preliminary designs of the selected concept(s).

3.8 MAN-MACHINE INTERFACE

The contractor shall develop a preliminary definition of the man-machine interface between the controller(s) and the manipulator boom(s). A preliminary definition of the required feedback information as well as the design of the master control station should be prepared.

3.9 PROPULSION PACKAGE REPLACEMENT

Assess the impact and desirability of utilizing a common T/O for station assembly and propulsion package replacement. Each propulsion package is visualized to include propellant and tankage, engine quad, and supporting structure. Only mechanical attachment and electrical connections will be required. A baseline weight of 600 pounds per package will be used. The shuttle launched space station can be assumed to include a minimum of four packages mounted either completely external to the form lines of the station (for example, at docking ports) or in recessed receptacles. One concept was defined in the prephase A study of a shuttle launched space station conducted by MSC. All placement operations will be conducted outside of the normally pressurized station volume.

4.0 PROGRAM MANAGEMENT REQUIREMENT

4.1 ORGANIZATION REQUIREMENTS

Not applicable.

4.2 CONFERENCE REQUIREMENTS

The contractor will be required to participate in reviews and interface meetings at other contractor's and NASA Centers. The MSC technical monitor, through the MSC contracting officer, will notify the contractor of those meetings he is expected to attend.

4.3 CONFIGURATION MANAGEMENT REQUIREMENTS

Not applicable

4.4 PROGRAM CONTROL REQUIREMENTS

Not applicable

4.5 CONTRACTOR DATA MANAGEMENT

The contractor will establish a system of management or utilize his existing data management function, if applicable, for the data called for in the SOW. The data management system will be capable of providing appropriate internal procedures for control of the collection, preparation, publication, quality, assessment, distribution, and maintenance of data.

The contractor will maintain as a ready reference for NASA a complete listing of all source documents utilized during the contract period of performance.

4.6 DOCUMENTATION REQUIREMENTS

4.6.1 GENERAL

The contractor will furnish all data items identified and described on the Data Requirements List (DRL), NASA Form 1106. The data items will be prepared in accordance with the Data Requirements Description (DRD), NASA Form 9, attached to the DRL and referenced on the DRL for each line of data specified thereon. Where practical, the contractor's own internal documents will be utilized to meet and/or supplement the requirements specified in the applicable DRD. Internal documents need not be retyped or reprinted prior to submission.

In addition to the data identified and described on the DRL, the contractor will furnish such other supplemental data as required by this SCW and attachments. Whenever such data items are identified, either by the contractor or NASA, they will be defined by DRD's and listed on supplemental DRL's to be subsequently furnished to or developed by the contractor.

4.6.2 DATA REQUIREMENTS LIST

Attachment 1 is a completed DRL with associated DRD's applicable to this SOW.

4.6.3 REPORTING UNITS

Final reporting will be in international units. English units will be in parentheses immediately following the international units.

4.7 INTERFACE REQUIREMENTS

Not applicable

4.8 FURTHER DEVELOPMENT PROGRAM

The contractor will provide an estimate of the resources required to design, develop, and manufacture the system and an example of a typical development schedule.

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5.0 SUPPORT REQUIREMENTS

5.1 GOVERNMENT-FURNISHED PROPERTY

Not applicable.

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6.0

QUALITY ASSURANCE

Not applicable.

7.0

RELIABILITY

In the conduct of this effort, it is expected that the contractor would normally search out critical weaknesses and provide appropriate corrective measures. It is therefore anticipated that the reliability requirements will not necessitate any significant increase in resources but will provide assurance that reliability techniques are being utilized as a design or study tool.

The contractor will include reliability factors; i.e., failure modes and effects on system performance, as basic elements of the trade-off studies to ensure equipment reliability and long life total systems performance. Single failure points should be identified. This effort should place emphasis on optimizing the approach to systems design, redundancy, maintainability. Reliability predictions and estimations may be useful in evaluating design trade-offs. A summary of the reliability efforts performed will be included in the final report.

The contractor will take appropriate measures to provide assurance that the resultant product will not preclude the efficient application of a more detailed reliability program for follow-on effort.

8.0

SYSTEM SAFETY

In the context of this study, it is expected that the contractor will normally identify safety concerns and provide corrective measures. It is therefore anticipated that for this contract, the system safety effort will be integrated with the design effort and/or testing, and will not require any significant increase in resources. To support trade-off studies, engineering assessments, or breadboard testing, the contractor shall search for hazards and provide resolutions so that any projected space flight equipment or prototype are designed with hazards eliminated or controlled.

Consideration shall be given to such aspects as fail operational/fail safe combinations, environmental extremes exceeding personnel and equipment tolerances, energy sources, electrical overloads and shock, inadvertent actuations, safety devices, nuclear radiation, flammability, toxicity, caution/warning devices, time constraints, emergency procedures, power source failures, and other critical malfunctions. The control of hazards shall include corrective measures in the following sequence or combinations thereof: design for minimum hazards, safety devices, warning devices, and special procedures. Uncontrolled or residual hazards shall be flagged for visibility.

The contractor is advised that his design will be subject to a more detailed system safety analysis in any possible follow-on extension or contract. Consequently, he shall pay appropriate attention to safety considerations to minimize subsequent downstream design/conceptual changes.

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9.0

APPLICABLE DOCUMENTS

Not applicable.

SPACE STATION AND SHUTTLE PARAMETERS

Appendix

Man Shuttle

Orbital Weight	68,038.5 Kilograms	(150,000 pounds)
Overall Length	37.3 meters	(122.5 feet)
Overall Height	11.6 meters	(37.9 feet)
Overall Width	27.7 meters	(90.8 feet)
Roll Moment of Inertia	1,054,013 Kilogram meter ²	(777,400 slug ft ²)
Pitch Moment of Inertia	6,114,332 Kilogram meter ²	(4,509,700 slug ft ²)
Yaw Moment of Inertia	6,324,891 Kilogram meter ²	(4,665,000 slug ft ²)

Large Shuttle

Orbital Weight	129,118.5 Kilograms	(284,659 pounds)
Overall Length	52.1 meters	(171.0 feet)
Overall Height	17.2 meters	(56.3 feet)
Overall Width	29.7 meters	(97.5 feet)
Roll Moment of Inertia	2,818,745 Kilogram meter ²	(2,079,000 slug ft ²)
Pitch Moment of Inertia	19,541,403 Kilogram meter ²	(14,413,000 slug ft ²)
Yaw Moment of Inertia	20,543,353 Kilogram meter ²	(15,152,000 slug ft ²)

Shuttle Launched Module for Modular Space Station

Weight	11,340 Kilograms (25,000 pounds)
Diameter	4.3 meters (14 feet)
Length	9.8 meters (32 feet)

SHUTTLE DOCKING CLOSURE RATES AND MISALIGNMENTS

Centerline Miss Distance	\pm 0.1524 meters (6 inches)
Miss Angle	\pm 3°
Forward Velocity	0.1219 meter/sec (.4 fps)
Lateral Velocity	0.0475 meters/sec (.15 fps)
Angular Rate	0.1°/sec