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DRL T-350
Line Item 4
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FINAL REPORT

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

(PRELIMINARY DESIGN)

Volume I - Management Summary

7 January 1972

Prepared For:

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

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Bollinger Canyon Road
San Ramon, California 94583

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FOREWORD

This final report presents the results of a four-month preliminary design study performed by MBAssociates 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. MBAssociates 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.

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TABLE OF CONTENTS

TABLE OF CONTENTS
Continued

LIST OF FIGURES

LIST OF FIGURES
Continued

LIST OF TABLES

1.0 SUMMARY

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 orientor 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. It is estimated that development of the basic manipulator system including delivery of one qualification unit and one flight unit, but without including ground support equipment or flight test support will require $17.4x10^6$ (±25%).

This study was divided into: Phase I "Concept Development and Selection" and Phase II "Concept Analysis". Initially the study objective was to establish a preliminary design for a space station cargo handling and docking system. However, it became evident during Phase I that high commonality existed between the requirements for a space station manipulator system and those for a shuttle manipulator system, and that potentially large savings in overall development and operational costs could be realized if a multipurpose interchangeable system was designed suitable for both applications. The study objective was modified accordingly.

The results of Phase I are briefly summarized in Appendix 5.0. The results of Phase II are summarized in Sections 2.0 through 4.0. A summary of the system weights and important weight trade-offs is presented in Appendix 2.0 and a summary of how the system meets the specified requirements is given in Appendix 3.0.

2.0 CONCEPT ANALYSIS

2.1 General Background

The initial objective of this study was to establish a preliminary design for a space station assembly and cargo handling system. However, it became evident during the concept selection phase that both shuttle and space station applications should be considered simultaneously because of the high degree of commonality and resulting development and operational cost savings that could be achieved. The possible commonality is as follows:

Common Elements	Different Elements
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	

A considerable effort was therefore devoted to optimizing commonality during both concept development and selection and subsequent analyses and refinement of the selected concept.

Space station assembly and shuttle cargo handling tasks were given emphasis in the concept analysis because they involve:

- Shuttle berthing (cooperative berthing of a large mass [113,500 Kg (250,000 lbs)]).
- Transferring the manipulator boom back and forth between the shuttle and station (interchangeability).

- Operation (control) of the boom from both the shuttle and station (common controllers and displays).
- Station assembly (a complicated task involving unloading the shuttle cargo bay and assembling the station modules).
- Cargo handling (transfer, handling and berthing of large [4.27m (15') dia x 17.2m (40') length] high mass [11,350 Kg (25,000 lbs) objects].

Consideration was also given to manipulator operations and supporting equipment required for the first ten (10) shuttle missions. Some of these missions involve only simple deployment and retrieval of small [less than 450 Kg (1000 lb)] passive satellites such as the Meteroid and Exposure Module. Others involve sophisticated retrieval, refurbishment and redeployment of fairly large [~4500 Kg (10,000 lb)] satellites such as the Large Space Telescope (LST). LST refurbishment will require special purpose end effectors which can unlock, remove, replace and re-lock equipment and experiment modules. The basic manipulator system which has been selected can accomplish all of the desired space station and shuttle based tasks considered by use of proper end effectors and auxiliary devices.

A cruciform space station and the 040A shuttle were used as reference configurations for the detailed manipulator system analyses. Their configurations and mass properties and a reference berthing port are presented in the appendix 1.0. Since the shuttle and other scientific satellites will be developed and deployed prior to development and deployment of the space station, estimates of the manipulator system development program have been phased with and are based on the shuttle development program.

2.2 Selected Concept and Ground Rules

The basic concept selected consists of the following:

- A single, 7 degree of freedom (DOF) symmetrical boom which can be used interchangeably on the shuttle and space station;
- An integral control station internal to the shuttle and station respectively with common controllers and displays in each;
- A dedicated auxiliary boom used for lights and viewing cameras;
- A stereoscopic, foveal, black and white and color television viewing system capable of providing manipulator operation without direct viewing in both sunlight and earth shadow condition; and
- A hard wire telecommunication system.

Auxiliary end effectors and other booms and supporting equipment can be used as required depending upon details of the particular mission involved.

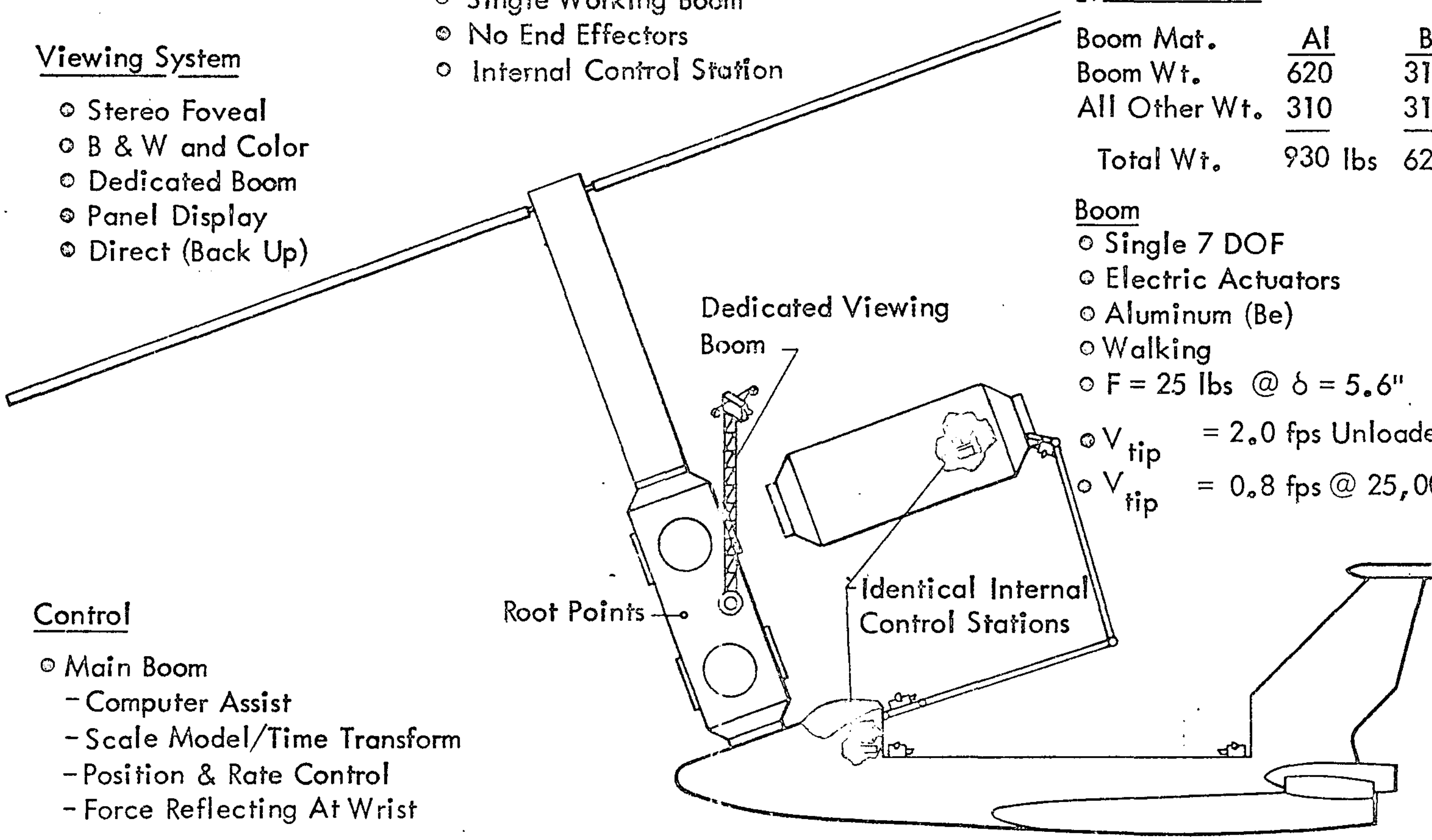
The ground rules specified for the analysis and preliminary design of the selected manipulator system were as follows:

- The boom diameter shall be equal to or less than 22.9 cm (9").
- Aluminum alloys are to be used for the boom structural material, although other light weight metals such as titanium should be considered.
- No separate manipulator power system is required; i.e., the shuttle or station power system can be used.

- Time sharing of the shuttle and station computers is to be considered.
- The root points for the manipulator boom on the space station side modules must be located at the ends of the modules.
- The weight of the root points and associated wiring required at various locations around the space station, shuttle, cargo modules, etc. will not be charged against the manipulator system.
- The weight of the total basic manipulator system shall not exceed 454 Kg (1000 lbs), including the control station. The basic system does not include general or special purpose end effectors, but must be capable of performing space station assembly, shuttle berthing, cargo handling and berthing and simple satellite deployment and retrieval.
- General and special purpose end effectors may be considered for accomplishing complicated and special purpose tasks.
- Space station and cargo modules [11,350 Kg (25,000 lbs)] are to be used as the design drivers on the manipulator boom design. The manipulator is to be designed for shuttle berthing, but the shuttle mass is not to be used as a design driver since the shuttle control system can be used to reduce the shuttle relative velocity low enough so that the kinetic energy to be absorbed in berthing the shuttle is less than that for berthing cargo or station modules.

2.3 System Description

The basic manipulator system is illustrated schematically in Figure 1 and it is shown in more detail in preliminary design drawings 0053ES0689, 0053ES0690, 0053ES0691, 0053ES0692, 0053ES0702 and 011432. (See Appendix 4.0 for 8-1/2x11 reductions of these drawings). Table 1 presents a weight breakdown of the major system components and Table 2 summarizes the boom design parameters. An effort was made to



Basic System

- Single Working Boom
- No End Effectors
- Internal Control Station

Viewing System

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

System Weight

Boom Mat.	Al	Be
Boom Wt.	620	310
All Other Wt.	310	310
Total Wt.	930 lbs	620 (lbs)

Boom

- Single 7 DOF
- Electric Actuators
- Aluminum (Be)
- Walking
- F = 25 lbs @ δ = 5.6"
- V_{tip} = 2.0 fps Unloaded
- V_{tip} = 0.8 fps @ 25,000 lb Load

Control

- Main Boom
  - Computer Assist
  - Scale Model/Time Transform
  - Position & Rate Control
  - Force Reflecting At Wrist
- Dexterous End Effector
  - Computer Assist
  - Position - Position Force Feed Back

Telecommunication

- State of the Art
- Hard Wired

FIGURE 1.
SCHEMATIC PRELIMINARY DESIGN OF MSC APPROVED MANIPULATOR SYSTEM

3361-9910

TABLE 1

BASIC MANIPULATOR SYSTEM WEIGHT SUMMARY*

Component	(Kg) Component	(Kg) Subtotals	(lbs) Component	(lbs) Subtotals
Dedicated Viewing Boom (with TV Camera & Lights)	---	53	---	117
Main Boom	---	281	---	620
Actuators (7)	105		231	
Clutches (7)	16		35	
End Connectors (2)	18		39	
Tubing	142		315	
Power System (1)	---	2.3	---	5
Control System (1)	---	2.7	---	6
TV System (2)	---	37	---	82
Control Console	---	45	---	100
TOTAL		421		930

* Based on Al as the primary boom reference structural material. It is estimated that the boom weight could be reduced to ≤ 141 Kg (310 lbs) by use of Be

Configuration

7 DOF

Symmetrical

Walking Type

Identical Electric Actuators

Mass Properties

Al 6061-T6

Length = 60'

Dia. = 9"

Thickness = 0.19"

Weight

Tubing	316
Actuators	231
Clutches	35
Connectors	39
	621 lbs

Load Capability

Tip Force* = 25 lbs @ δ=5.6"

Bending Stiffness = 4.6 lb/in

Torsional Stiffness = 9.8 in-lb/deg

*Actuators OK to ≈ 50 lbs

Fundamental Period - Fully Extended Boom

Load (1)		Period (Secs)	
Type	Weight (lbs)	Bending	Torsion (2)
None	0	2.0	0.04
Station Module	25,000	23	8
Cargo Module	65,000 Max	38	20
Mini Shuttle	150,000	50	61
Large Shuttle	250,000	65	110

(1) Load Attached @ CG

(2) Torsion in yaw for payloads

Thermal Distortion

All Black Surface	With Thermal Shield
α/ϵ = 1.04	$\epsilon_{\text{Shield to Boom}}$ = 0.1
Max Deflection = ± 14 in	Max Deflection = ± 1.4 in
Time Constant ~5 min	

Tip Speeds

υ (unloaded) = 2.0 fps

υ (25,000 lbs) =0.8 fps

TABLE 2
SUMMARY OF BOOM DESIGN PARAMETERS

make all components except the boom as light as possible and then to use the remaining weight balance for the boom in order to obtain the best combination of large tip force and small deflection. However, as can be seen in Table 1, the entire 454 Kg (1000 lbs) allowance was not used since a tip force of 111 N (25 lbs) with a deflection of only 14.2 cm (5.6") could be achieved and it was believed that a weight margin should be provided to accommodate weight growth as components are better defined by detailed design. The boom and actuators are capable of exerting a tip force of approximately 222 N (50 lbs) but the deflection would also double to 35 cm (12"). A 14.2 cm (5.6") deflection was assumed as a reasonable limit on deflection since the anticipated allowable berthing misalignment is $\pm$ 15 cm (6"). Aluminum was selected as the reference boom structural material with beryllium (or a beryllium alloy) as a strong potential candidate. Except for beryllium, an aluminum alloy tube can be made as light (or lighter) than other candidate light weight metal alloys for the same boom diameter, length and tip deflection since the boom is deflection rather than stress limited. Beryllium, or beryllium alloys, offer the possibility of reducing the boom weight by a factor of ~2; however, beryllium is very crack sensitive and its use depends on detailed design analysis in conjunction with fatigue/crack sensitivity testing.

Similar electromechanical actuators were selected for all joints of the main boom since a single actuator concept could be configured to fit within the required envelopes and provide the rotation necessary for all joints. Use of a common actuator type will reduce development and fabrication costs, enhance reliability and simplify logistics. The selected actuator concept is illustrated in Figure 2. It consists of two direct current motors each driving a separate gear box and differential gear. Torque is transmitted from the output side of the differential gear to one member of the joint through a multiple disc clutch. The clutch slips if the boom is forced beyond the set torque limit of the actuator and also may be disengaged if one of the drive motor/gear trains should fail. The joint position encoder is located on the boom side of the clutch so that joint position/registration is not lost if a clutch slips (see Drawing 0053ES0690

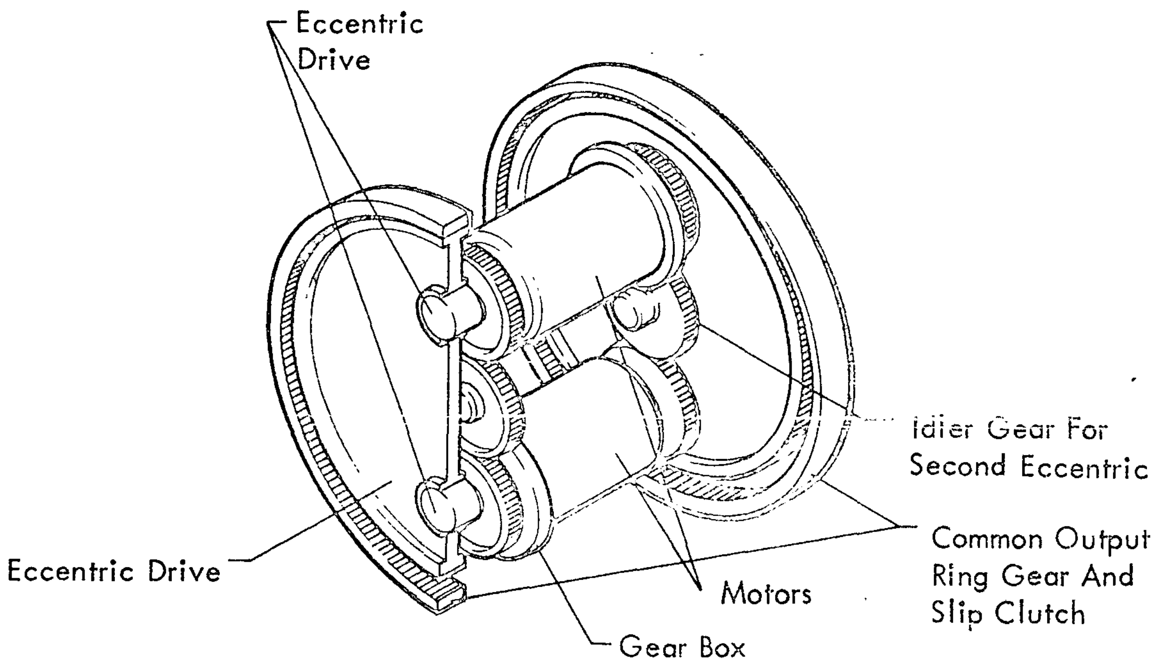


FIGURE 2.
SCHEMATIC OF SELECTED DOUBLE
DIFFERENTIAL GEAR ACTUATOR CONFIGURATION

Appendix 4.0 for further details). It should be also noted that when a clutch is forced to slip by overloading, it becomes an effective energy dissipating device.

The boom is symmetrical about the elbow and has a total of 7 DOF's - one at the elbow and three at each "wrist" assembly. The arms of the boom are 8.15 m (26.4') long and the wrists 1 m (3.24') long for a total length of 18.3 m (60'). The boom kinematic arrangement is shown in Figure 3. The elbow and nearest wrist joints are arranged with their axes parallel so that the joint motions all lie in the same plane. The elbow joint is arranged so that the boom can fold back on itself. The middle wrist joints are pivots whose axes are perpendicular to the above axis and the wrist element. The outermost wrist joint has its axis parallel with the wrist element and provides wrist roll.

The boom joint configurations have been selected in accordance with five rules developed in this study based on past experience with a variety of manipulator designs. These rules are summarized in Appendix 6.0 in this volume and are discussed in detail in Volume II "Concept Selection".

The end of the wrist terminates in a connector that fits into and locks with a root point. Space station or shuttle power is used to power the manipulator. All power, control signals and television signals are transmitted to the boom through mating electrical connectors in the root point and boom end connector. The root points and end connectors are illustrated in Figure 4.

The boom may be operated from either end. During normal operation, the middle "shoulder" joint is locked and used only as an indexing joint. The boom controls are arranged such that the boom always looks the same to the operator, no matter which end is plugged in. The boom can move about the space station or shuttle or can be transferred back and forth between the shuttle and station by walking "end-over-end" from one root point to another. Proper connection to the "new" root point is always confirmed before the old one is released.

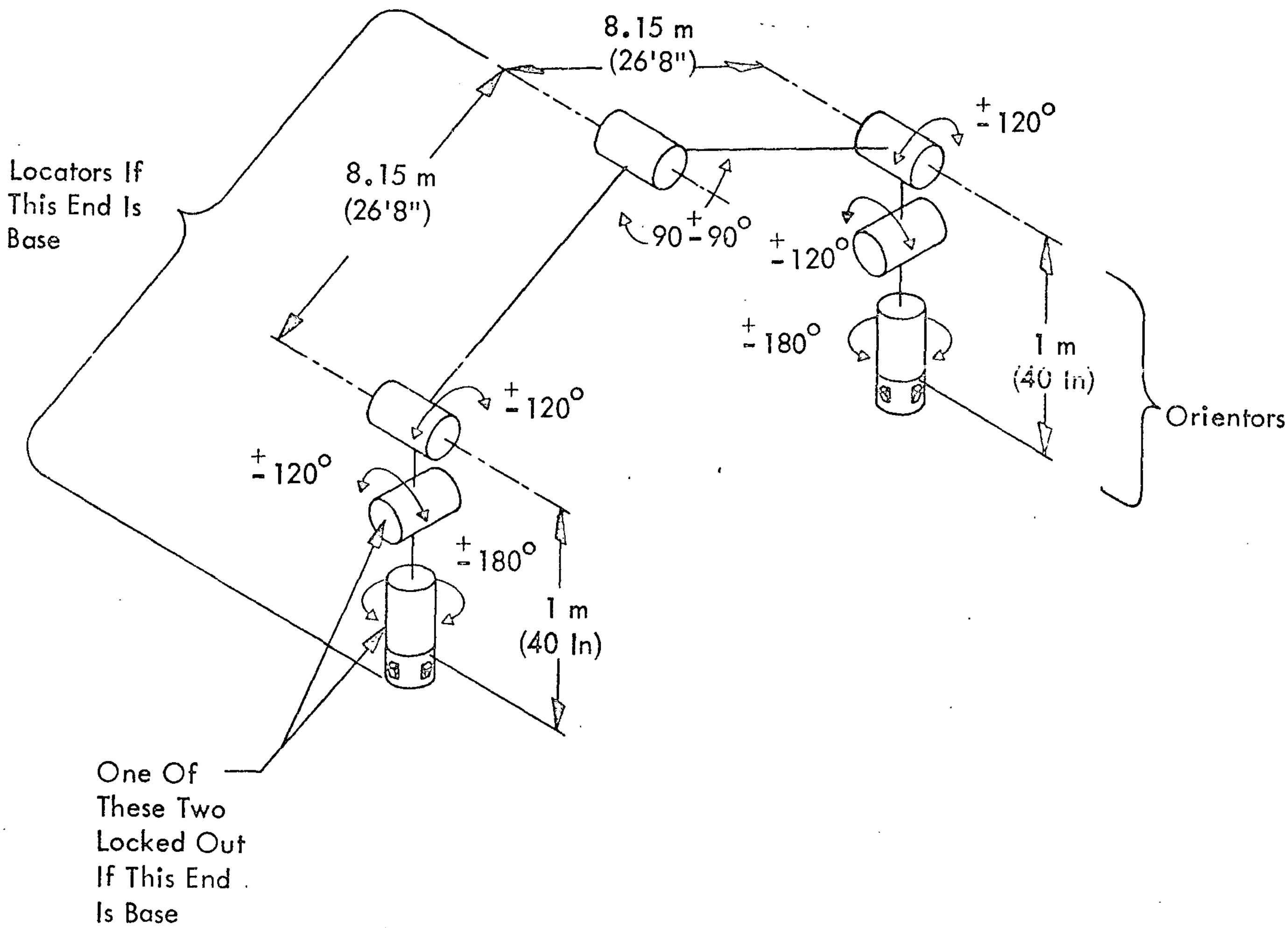


FIGURE 3.
KINEMATIC ARRANGEMENT OF SELECTED SYMMETRIC
BOOM-JOINT CONFIGURATION

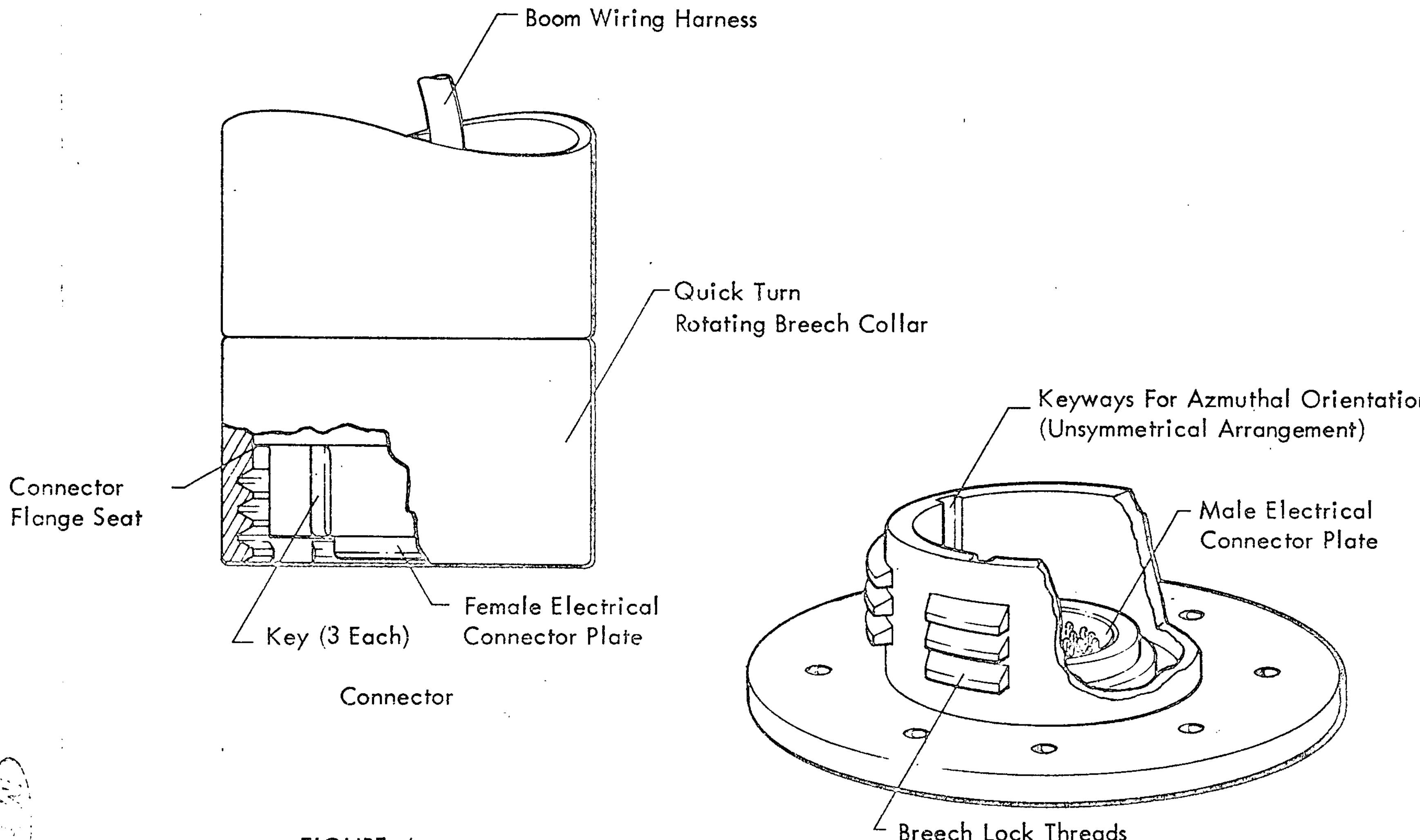


FIGURE 4.
SCHEMATIC ROOT AND END CONNECTOR

Power for actuators, lights and cameras is transmitted through the boom on a bus. Power amplifiers, A-D converters and buffers for each actuator are co-located with the actuator. Control and monitor signals are transmitted by a parallel wire, pulse code modulated system. Television signals are transmitted in analog form through coax cables. The maximum power requirement of the manipulator system is approximately 2 Kws.

The visual system has been designed for a broad spectrum of tasks ranging from simple cargo module handling (for which a monocular single field TV system may be adequate) to precise, dexterous repair tasks (for which a stereo, high resolution TV system is required). The system consists of two cameras mounted on the main boom, a single camera mounted on the dedicated viewing boom and small auxiliary cameras located strategically about the station or shuttle as required. The cameras on the main boom and dedicated viewing boom are stereoscopic, foveal systems which can display in black and white for normal operation and color (by use of a color wheel) for inspection. These cameras also have automatic focus and convergence and a controlled zoom capability. The auxiliary cameras are small [~2 Kg (5 lb) including illumination lights], black and white only and have a variable field. The boom cameras each have three 500 watts incandescent lights which may be used singly or together. The auxiliary cameras have a single 500 watt incandescent light. The viewing boom is a light weight extendible astromast type boom having three locator and three orientor DOF's. The locator DOF's consist of two shoulder joints and the boom extension. The three orientor joints are at the distal end of the boom and provide pan, tilt and roll motions for the camera/light assemblies. The viewing boom has a shoulder end connector which mates with the main boom root points. The viewing boom also has a root point on its side near the shoulder so that the main boom may move the viewing boom to desired root points.

The man/machine interface (control station) has been designed for maximum commonality between the shuttle and space station. Direct viewing will be possible for many shuttle/manipulator operations whereas the station may have no direct viewing capability. With the exception of providing for direct viewing on the shuttle, it is desirable to have identical control console layouts to minimize operator training and confusion. The shuttle crew compartment is more confining than the space station crew module. Thus, the approach used was to lay out the control console within the shuttle constraints, to take advantage of the direct viewing possible on the shuttle and to provide panel video displays satisfactory for precise, dexterous tasks. The physical layout of the manipulator control station in the 040A crew compartment is illustrated in Figure 5. The manipulator controllers and the control panel layout are shown in Figures 6 and 7 respectively. One primary display and two secondary displays may be displayed simultaneously. Furthermore, the operator may switch different cameras into each of the several displays. Control of the primary cameras is achieved by an occulometer type eye controller using coded signals. Several control modes are used for the main boom depending on the task involved, but for all except emergency operations, control is achieved through a computer.

For capture operations, the boom is preset to a desired preliminary capture configuration. The viewing cameras are then oriented so that the scenes presented on the console displays are placed in a preferred orientation relative to the operator x-y-z frame of reference. He then controls the boom with the right hand 6 DOF controller in an end point rate control mode. He moves the controller in an x-y-z coordinate system relative to his display and the computer performs a coordinate transformation to drive the boom tip and wrist assembly in accordance with his commands. The 3 wrist joints (orientor DOF's) have force reflecting feed back to provide operator feel for engagement of the captive socket. The maximum relative capture velocity has been specified as .122 m/sec (.4 fps). The boom actuators have been designed to drive the tip at 5 times [.61 m/sec (2 fps)] the maximum capture velocity in order to readily outmaneuver the capture object.

For gross translation operations, the operator uses the small scale model controller and a similarly scaled model of the shuttle/station/

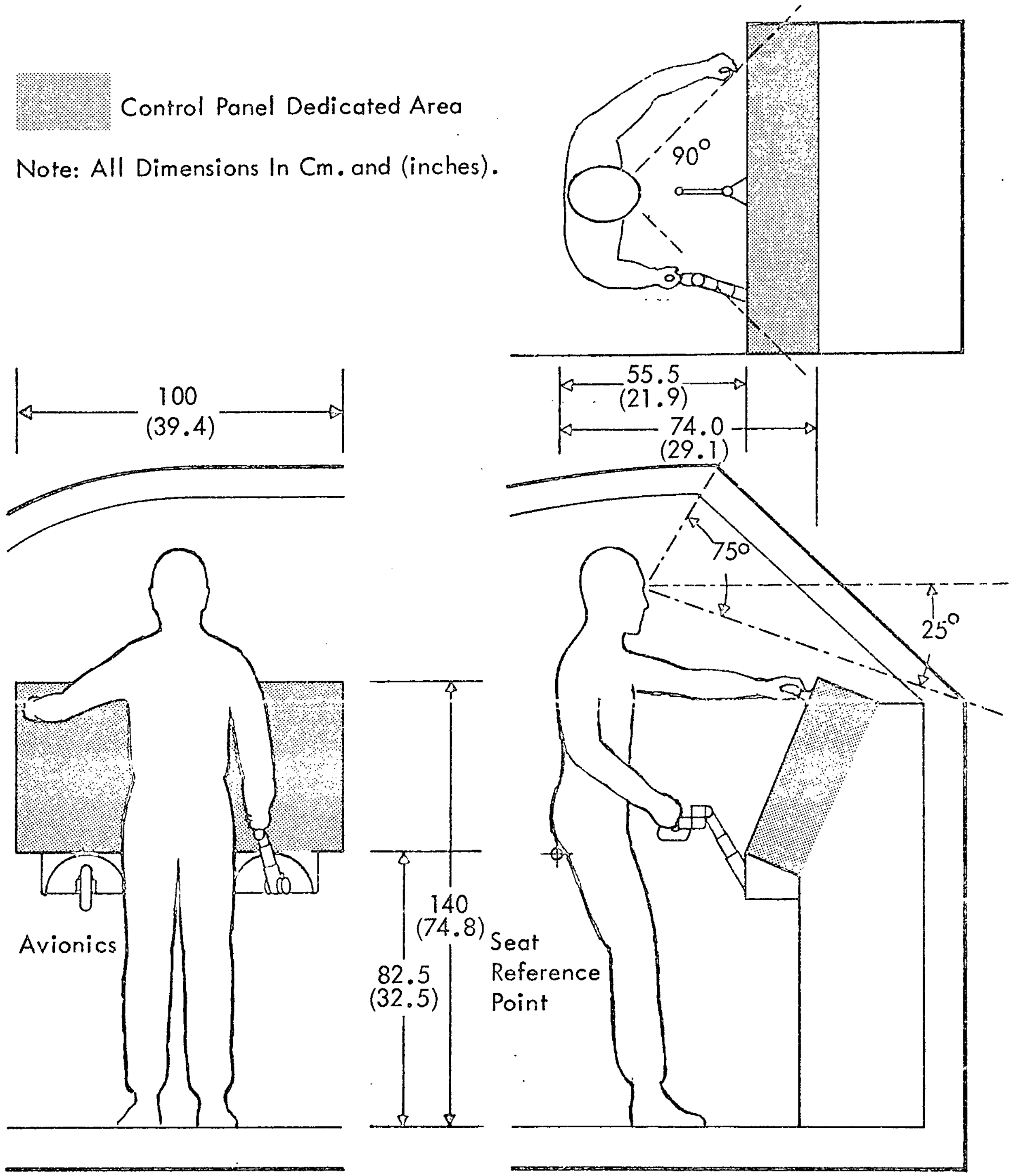


FIGURE 5.

MASTER CONTROLLER USED FOR DEXTEROUS END EFFECTOR CONTROL

0072-10011

Note: Master Controllers Have $x, y, z, \theta, \phi, \gamma$ Movement Capability. Additional Functions Can Be Provided By Button Actuators On Grip.

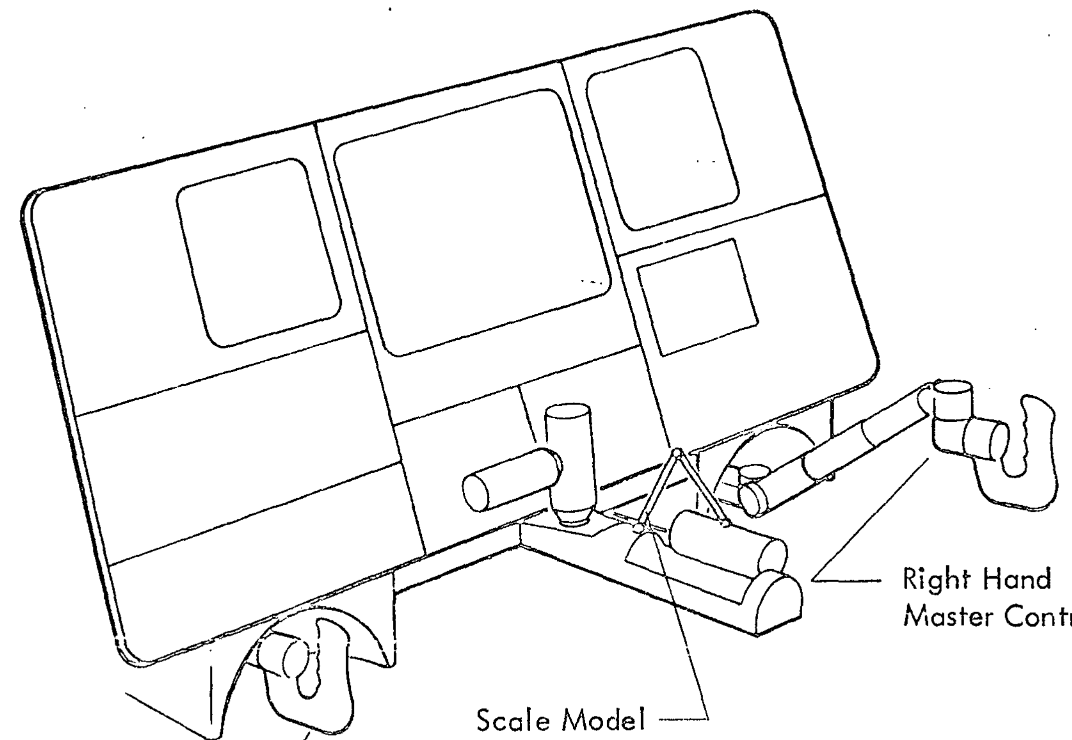


FIGURE 6.
LAYOUT OF MANIPULATOR CONTROLLERS

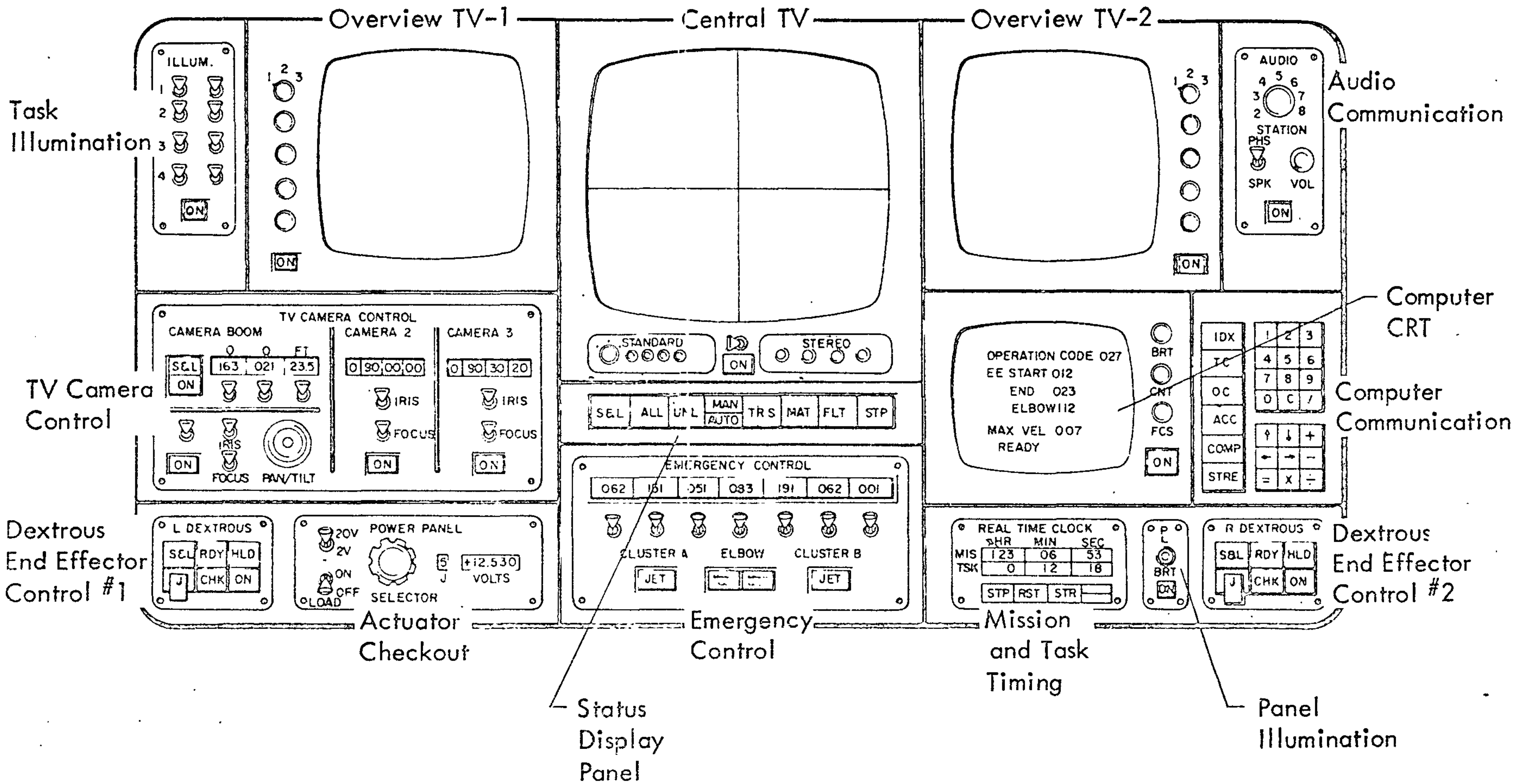


FIGURE 7.
MANIPULATOR CONTROL PANEL LAYOUT

payload configuration. He first lays out the models in their proper relative orientations for the beginning of the operation. Then he moves the model boom through a trajectory to the desired end point configuration. The model boom joint histograms are recorded by the computer, smoothed, checked for collisions with obstacles and optimized if desired. When the computer indicates that all is ready, the operator can command execution of the maneuver which is then done by the computer. Feasibility of this control technique was demonstrated by simulation studies with a model controller, a computer and MBA's Naval Anthropomorphic Teleoperator (NAT) mechanical arm. (See Volume IV "Simulation Studies"). For final berthing operations, the operator controls the boom in a rate control mode similar to the capture operation described above. For operation of a dexterous end effector, the operator will use both 6 DOF controllers in an end point wrist/grip assembly, position-position bilateral force feedback control mode. As in the case of the capture operation, he will orient his primary viewing camera to obtain the desired field-of-view and work scene orienttation. He can then move the controllers in an x-y-z coordinate system relative to his frame of reference and the computer will do the necessary coordinate and force transformations to provide the desired bilateral motions and force feedback. A single 6 DOF controller can be used for operation of other special purpose end effectors in a manner similar to boom capture and berthing operations.

2.4 System Utility

Table 3 summarizes the utility capability of the basic manipulator system and of this system with special end effectors and auxiliary devices. Many tasks can be accomplished with the basic manipulator (which includes no end effectors) by the simple expedient of configuring the attachment point(s) on the objects to be handled as a standard manipulator root point. Satellite deployment can be accomplished with the basic system and the power and parallel PCM data busses can be used for final satellite checkout and activation during such deployments.

Special end effectors are required for satellite retrieval; i.e., it is better to use a grabbing type (claw) female end effector than a male expanding type (the boom end connector) to minimize "pushing" the satellite away during capture. The station maintenance, repair and propulsion package replacement can be accomplished with a single boom and appropriate end effectors by using station root points as transfer and holding receptacles. For more complicated tasks requiring dexterous, force reflecting end effectors, the end effectors can be equipped with special grapling arms to provide the platform stability (rigidity) required for accomplishing the task.

Satellite erection, servicing and resupply tasks require an auxiliary device on the shuttle to hold the satellite as well as specialized end effectors on the main boom for accomplishing the task. If the shuttle is equipped with a berthing port it might be used as the holding device or a rotating turnstile might be attached to the part to hold and position the satellite. In some cases, such as servicing the Large Space Telescope (LST) it is desirable to hold the satellite away from the shuttle to avoid possible contamination of the optics by outgassing from the shuttle. An auxiliary boom or self-erecting scaffold could be used for this purpose. It is also of interest to note current plans for the LST resupply call for a force of $\sim$ 908 Kg(2000 lbs) to extract and re-install service and experiment modules. It is not practical to design a boom to provide such a force, how-

TABLE 3

SUMMARY OF MANIPULATOR SYSTEM UTILITY

CONFIGURATION	POSSIBLE TASKS	REMARKS
Basic System (single working boom without end effectors)	Shuttle Berthing Station Assembly Bulk Cargo Transfer(Cargo Modules) Satellite Deployment	Manipulator Root Points Used as attachment point on all objects.
Basic + End Effectors	Satellite Deployment and Retrieval Station Maintenance and Repair Propulsion Package Replacement	Claw type end effector preferred for satellite deployment and required for satellite retrieval.
Basic + End Effectors + Auxiliary Devices	Satellite Erection(i. e., solar panels) Satellite Service and Resupply	A second working boom could be used as an "auxiliary device"

ever it can be accomplished, with the proper type of end effector as described below.

No exacting task times were either specified by NASA or derived during this study. A general rule was used that a task, or major elements of it, should be accomplished in a time equal to a half orbit period or less, to minimize variations in illumination.

Boom tip forces of 4.54Kg (10 lbs), or even less, are adequate to translate and orient cargo modules (the specified design drivers) in times of like 10 minutes or less. If berthing, deberthing and other manipulative tasks could be accomplished with such low tip forces, there would seem to be no requirement for large force levels. However, it is difficult to predict possible friction or jamming effects which may arise during berthing, deberthing, or other object mating or extraction operations. Thermal distortion, vacuum welding and emergency situations may also require occasional use of high force levels. Therefore, the approach used in the present design study was to achieve as large a force level as possible consistent with total system weight limits and reasonable boom deflection even though specific (large) force requirements could not actually be identified in the utility analyses. Furthermore, by emphasizing a maximum practical tip force capability, the reliability/utility level of the boom can be increased. In the event of failure of one of the two actuator drive motors, the boom can still operate at acceptable force levels (1/2 of maximum) at that actuator. It should also be noted that the non-backdriveability of the actuators (a consequence of friction at the large gear reductions required) allows actuators with such a failure to sustain full design loads if the actuator is not active (driving).

Specific manipulator operations, end effectors and auxiliary devices for station assembly and maintenance and LST servicing are presented below. Additional considerations of Utility, including possible shuttle root point locations and viewing windows, are presented in Volume III, Section 6.0 "Technical Discussion".

2.4.1 Servicing the LST

Possible manipulator root point locations on the shuttle are illustrated in Figure 8. A rotary root point extension can be used to swing the shoulder from a side located storage position to a raised vertically centered operating position. (It would be out of the way of both the manipulator and space vehicle operator's view in this location.) Two additional fixed root points are located, one midway down the cargo bay (in the fixed door sills which are exposed when the cargo doors are swung open) and, the other, on the aft bulkhead. Such an array provides complete mobility around the cargo bay to better access work areas.

Figure 9 illustrates the use of the above root point array, an auxiliary scaffold (mast) and a special purpose end effector to exchange modules on the LST. The LST would be retrieved by the manipulator boom and placed on a rotatable pedestal on the end of the auxiliary mast. The mast would be located in the aft region of the bay to place the LST in a more optimum viewing position. The LST would be held as far as possible away from the shuttle to minimize contamination of the optics caused by shuttle outgassing. The boom would be transferred to the mid bay position to obtain better accessability to the LST modules. The special end effector is configured to latch on to a module and at the same time engage actuators with the module fasteners. The actuators can provide the large force required to release (and re-fasten) the modules from the LST without placing loads on the boom. When the module is released, the boom would extract it, place it in the storage rack and re-insert a new module. Direct viewing is indicated, however, a simple TV camera may be required to facilitate aligning and latching the end effectors on the modules.

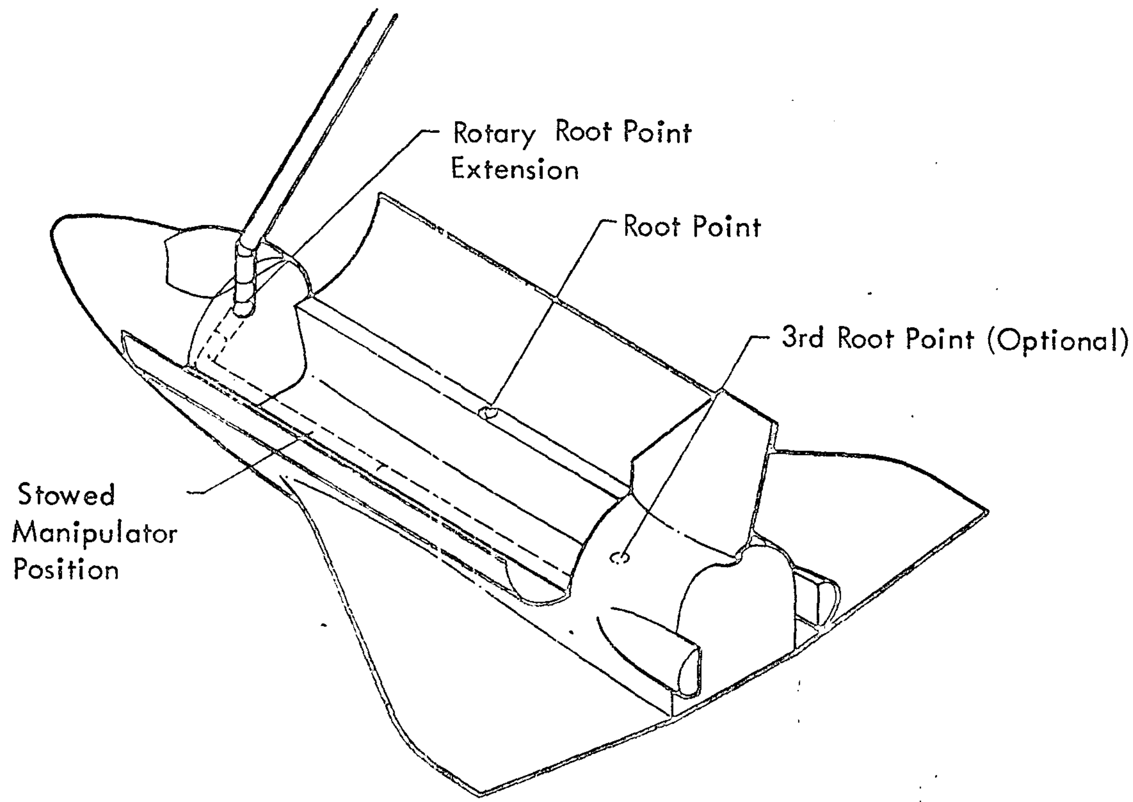


FIGURE 8.
SHUTTLE SWING ARM AND FIXED ROOT POINT LOCATIONS (2)

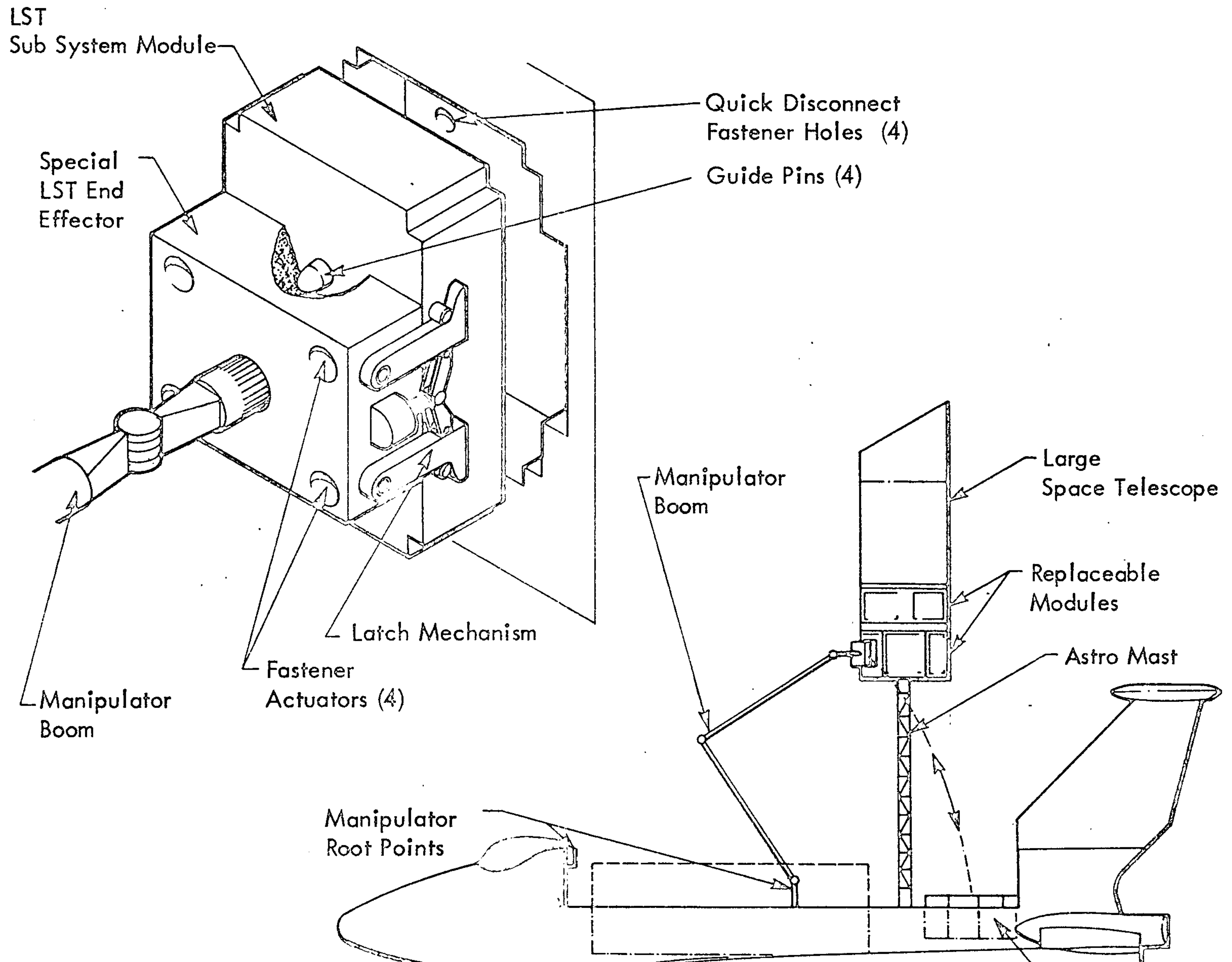


FIGURE 9.
LARGE SPACE TELESCOPE SUPPORT AND END EFFECTOR

2.4.2 The First Ten Shuttle Missions

Table 4 summarizes the first 10 shuttle missions and the possible manipulator requirements. The LST mission described above represents shuttle mission #6. The first mission, deployment of the meteoroid module (an inert gravity gradient stabilized satellite) can be deployed by use of a simple claw type end effector. Mission #2 is unknown. Mission #3 would use the equipment described above for the LST. However, the LST mirror test unit would be carried to orbit by the shuttle as indicated by the dotted line cargo in Figure 9. Mission #7 would require a large claw which may or may not be the same as Mission #1. Missions #8 and #10 will not deploy or retrieve any satellites. Mission #9 might use the same claw as Mission #1. The visual requirements have not been examined in detail but it is anticipated that at least a single field, monocular, black and white TV camera will be required.

2.4.3 Space Station Assembly and Maintenance

Figure 10 illustrates the assembled space station including the core module, solar array power module, crew side modules, cargo modules and air locks. Also shown are typical manipulator root points: 5 on each side module, 4 on the core module, 2 on the power module and 2 on the air locks. The manipulator is shown performing a repair operation on the solar array to illustrate the mobility and reach achieved by the root point array/walking boom concept.

A scale model of the space station modules and the shuttle crew compartment/cargo bay were made to study manipulator kinematics and station assembly techniques. The photographs in Figures 11, 12, 13, 14 and 15 illustrate the way in which the manipulator can be used for station assembly and maintenance. Note the root points used for each module. The manipulator would be carried with the shuttle until the station is manned (after the station control/crew module is attached). Thereafter it would remain with the station.

Mission No.	Purpose	No. of Manipulator Booms Required	End Effector Type	Auxillary Equipment	Comments
1	Deploy Meteoroid Module	One	Claw Type Hand Grip	None	None
2	DOD Mission	Unknown	Unknown	Unknown	Mission Type Unknown
3	Large Space Telescope Mirror Test	One	Module Holder Release/Fasten Mechanism	Astromast Support Structure	Manipulator And End Effector Only Needed To Practice Mission 6
4	Deploy Astronomy Explorer Retrieve Meteoroid Module	One	Same As Mission 1	None	None
5	Deploy HEAO - D	One	Same As Mission 1	None	None
6	Visit Intermediate Large Space Telescope	One	Same As Mission 1 & 3	Same As Mission 3	None
7	Deploy/Retrieve Bioresearch Modules	One	Large Claw	None	The Large Claw Will Make Satellite Capture Easier
8	Infrared Telescope Sortie	None	None	None	None
9	Systems Test Satellite Launch	One	Same As Mission 1	None	None
10	Earth Observation Sortie	None	None	None	None

TABLE 4
FIRST TEN SHUTTLE MISSIONS - MANIPULATOR REQUIREMENTS SUMMARY

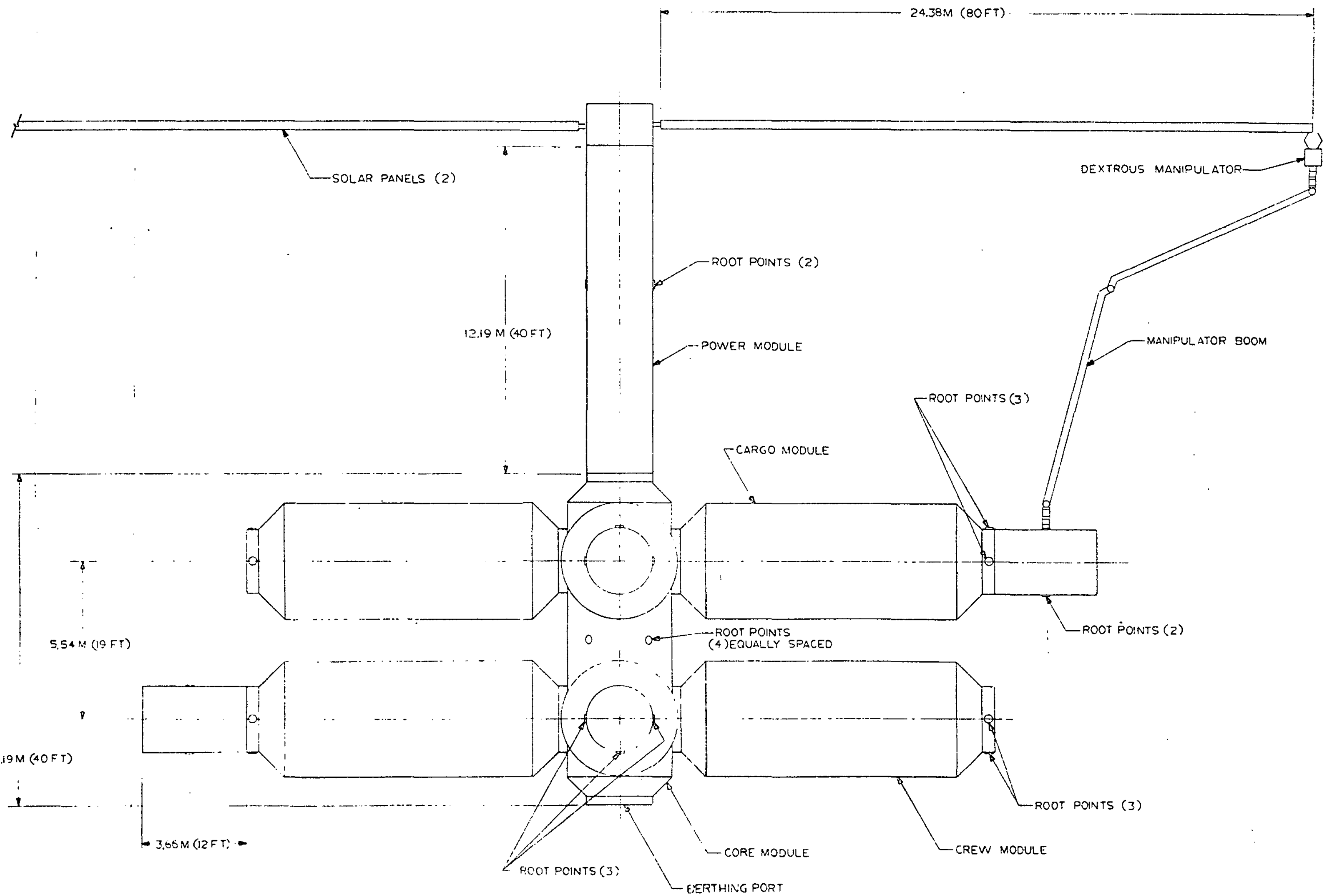


FIGURE 10
ASSEMBLED SPACE STATION SHOWING ROOT POINTS AND MANIPULATOR

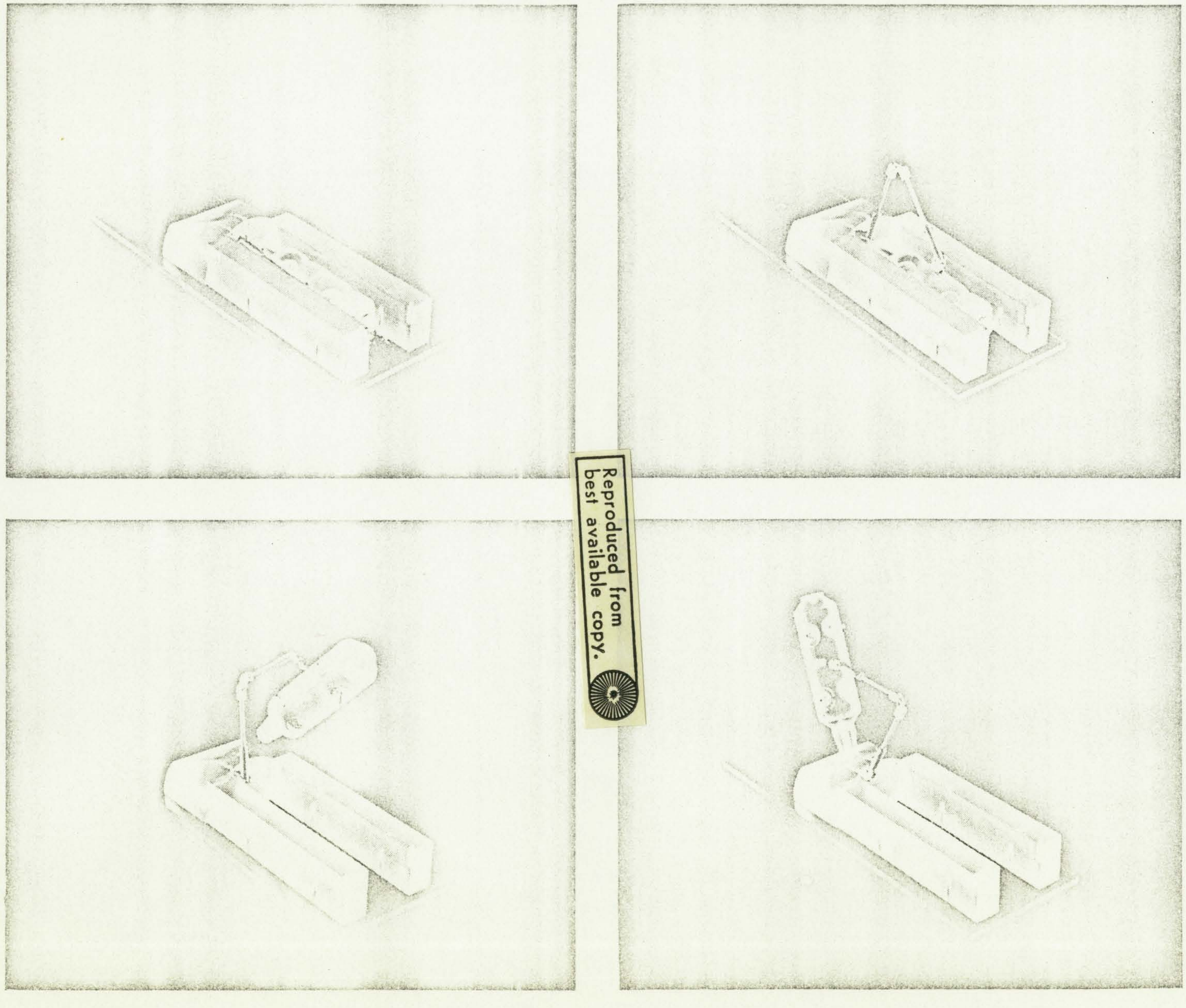


FIGURE 11.
CORE MODULE DEPLOYMENT

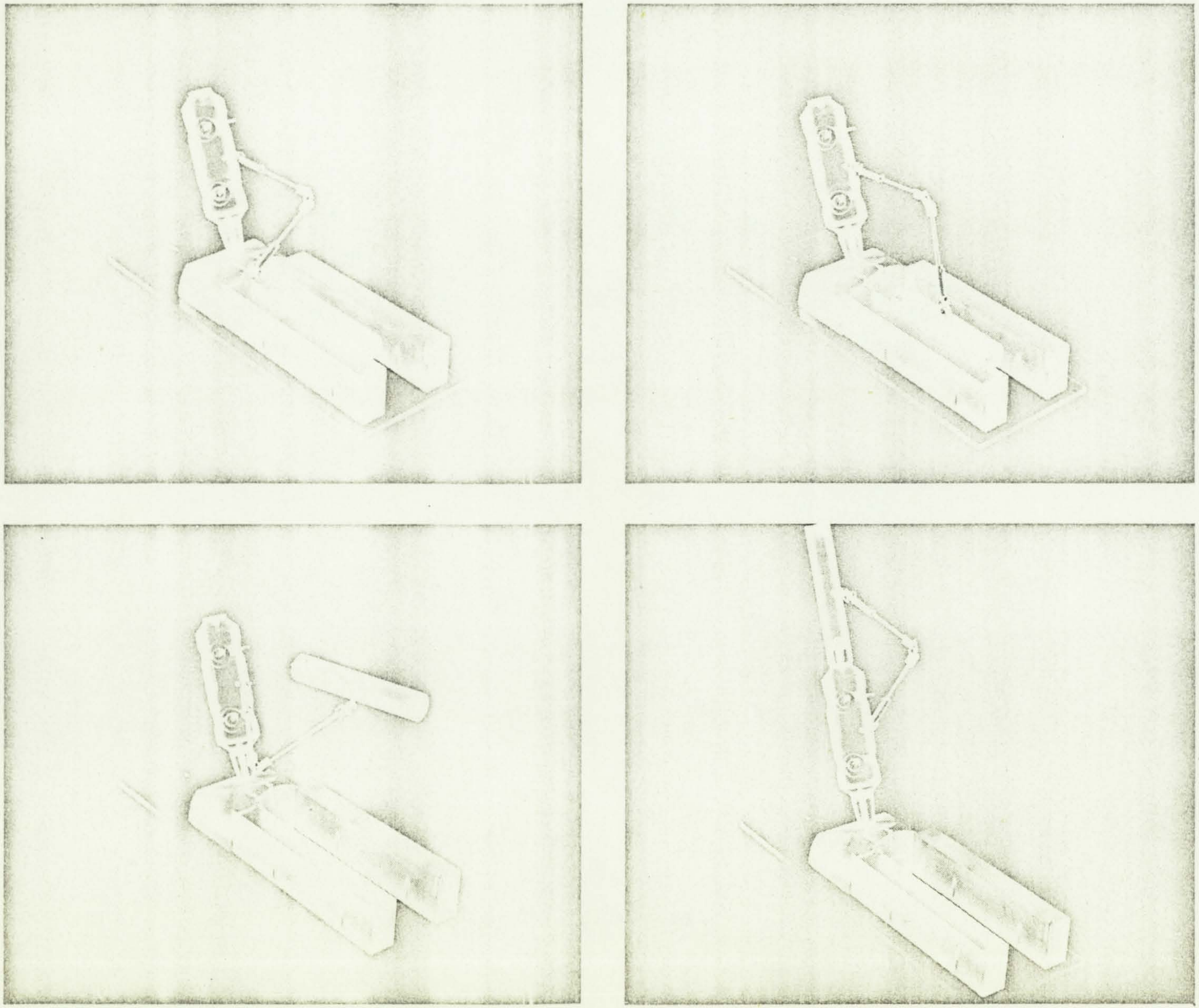


FIGURE 12.
SOLAR PANEL/POWER AND CORE MODULE ASSEMBLY

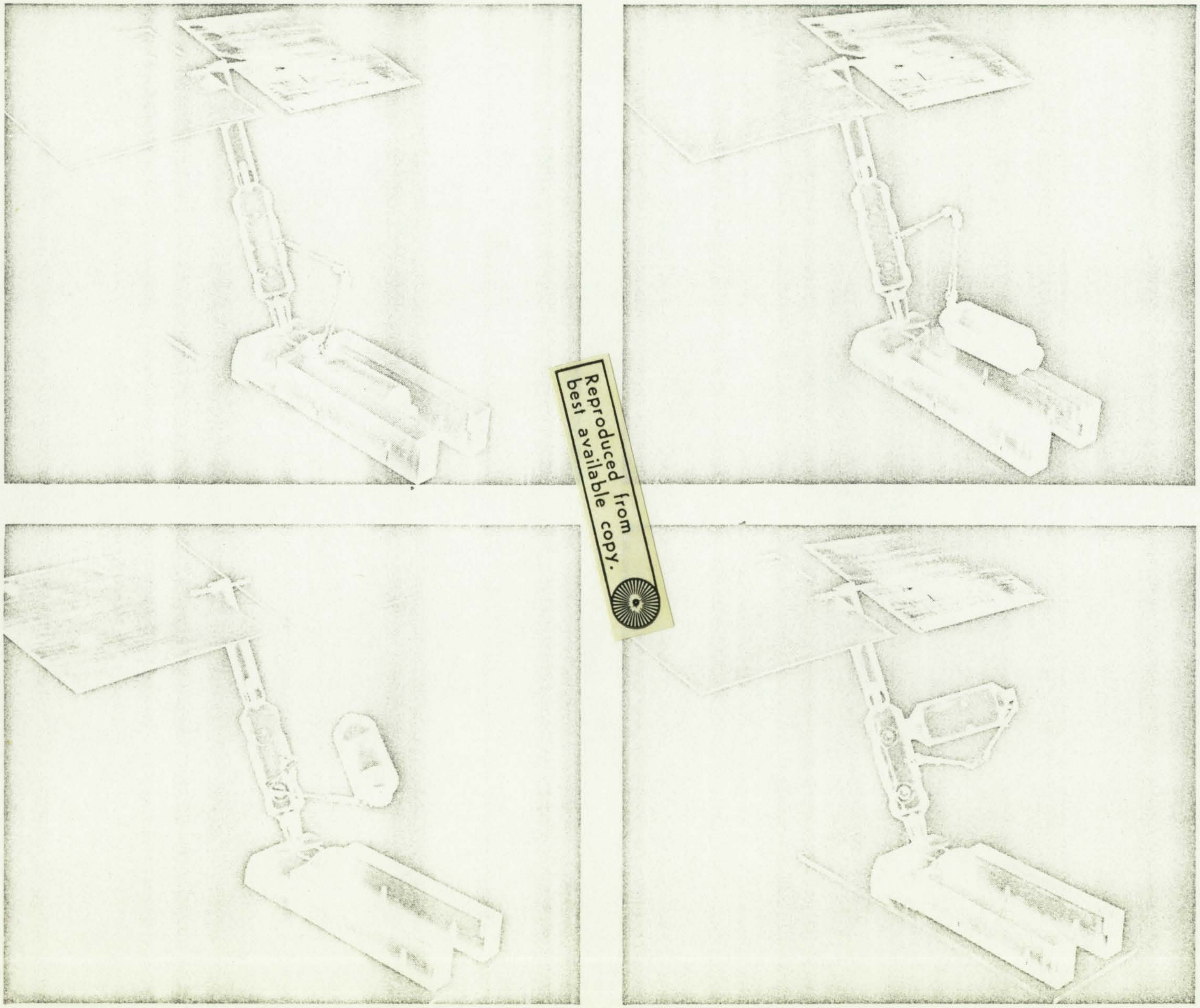


FIGURE 13.
CONTROL/CREW MODULE TO CORE ASSEMBLY

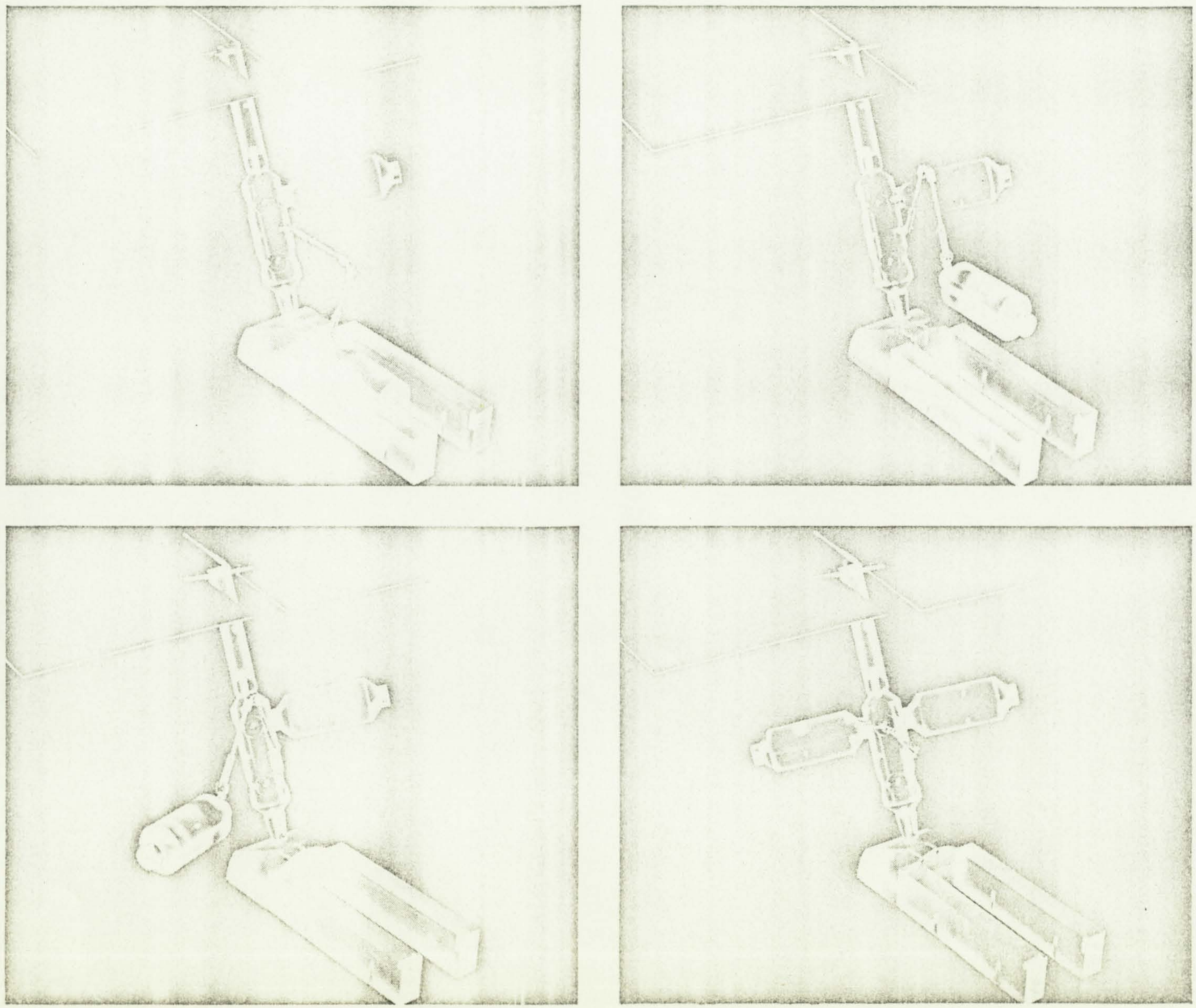


FIGURE 14.
MODULE ASSEMBLY (FORWARD POSITION)

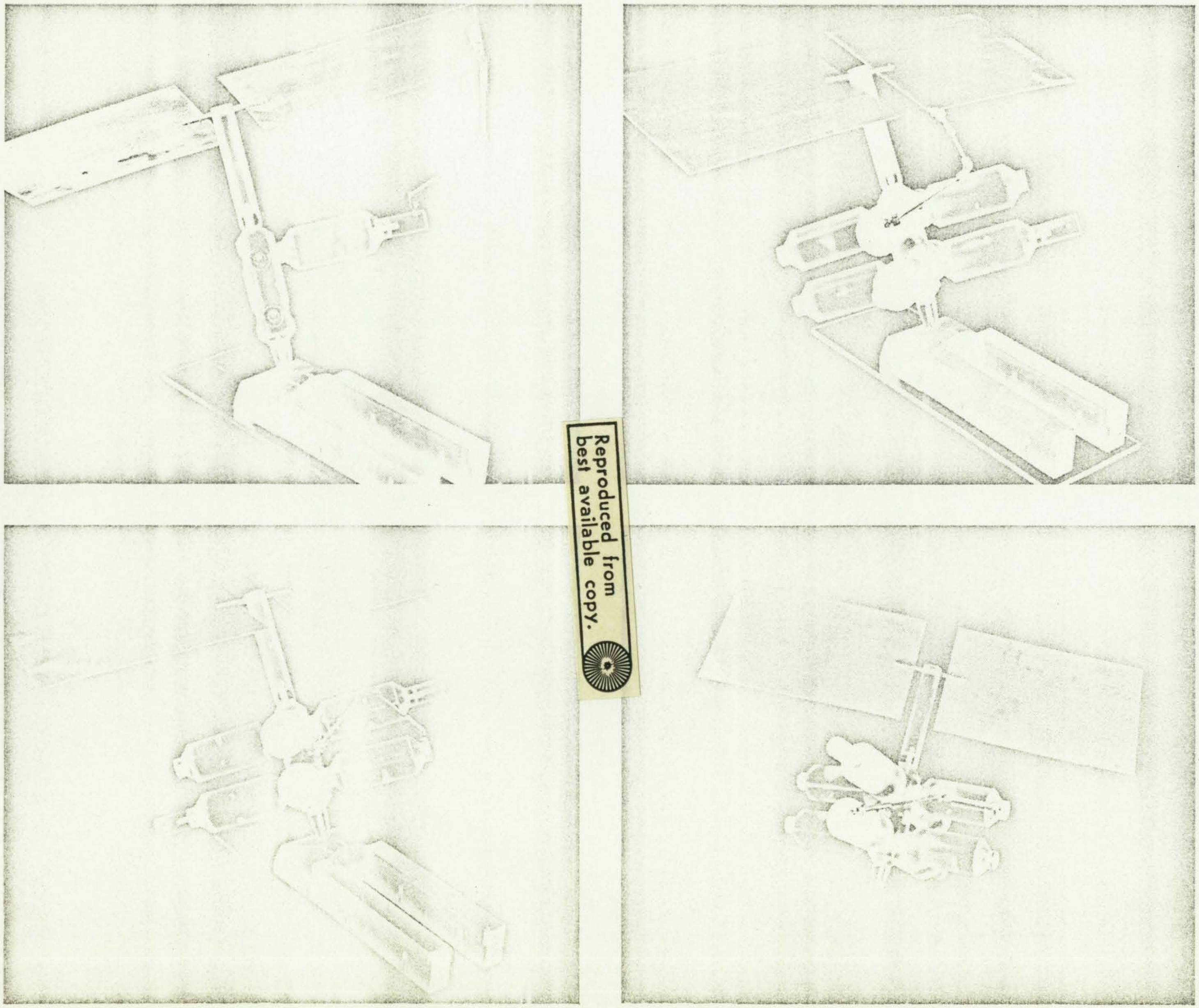


FIGURE 15.
WALKING BOOM AND MAINTENANCE

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Figure 13 shows the crew module being manipulated using the outer root points. Figure 14 shows a side module being manipulated using an inner (forward) root point. The utility and mobility of the manipulator are enhanced by having root points at each end of the modules. It should also be possible to use the root points as cargo tie-down points for transporting the modules in the shuttle. Figure 15 illustrates the way in which the boom can walk around the station for inspection, maintenance and repair operation.

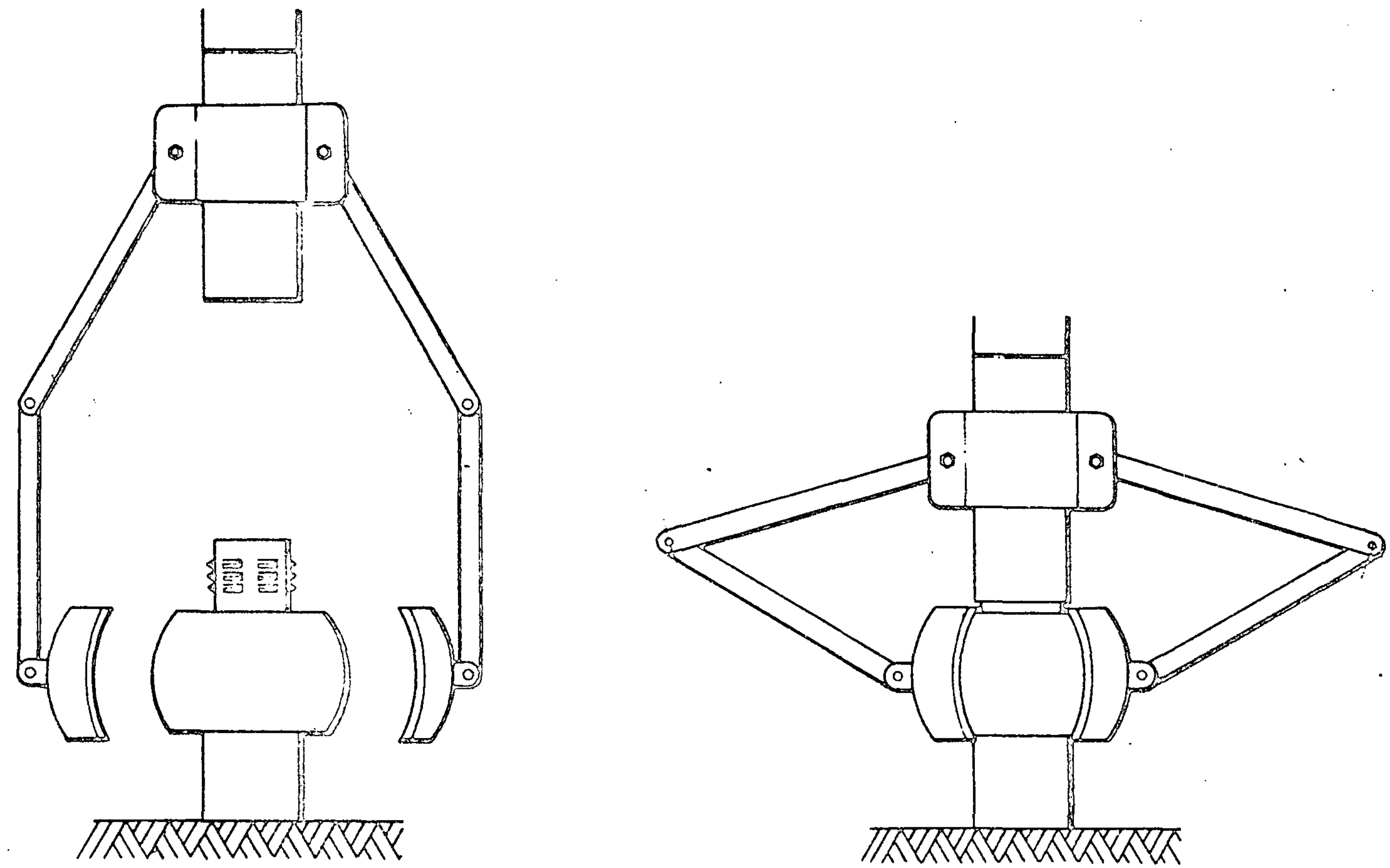
2.4.4 Shuttle Capture

The ground rule (see Section 2.2 "Selected Concept and Ground Rules") for shuttle capture is to: (1) accomplish "capture" at a relative shuttle/station velocity of .12m/sec (0.4 fps); (2) allow the shuttle ACS/ propulsion system to reduce the relative velocity to 0.03m/sec (0.1 fps) by using boom position and rate information fed into the shuttle control system (i.e., the boom is allowed to "float") and; (3) complete shuttle arrest from 0.03m/sec (0.1 fps) by use of manipulator forces.

Several approaches to shuttle capture within the above ground rule can be taken. The reference approach is to mate the boom end connector directly with a root point on the shuttle. As soon as the boom is connected to the root point, boom position and rate data can be fed into the shuttle control system. This approach will require a degree of operator skill and a fast acting connector actuator.

A second approach is to use a special,quick grasping end effector and a compatible shuttle root point as shown in Figure 16. As soon as the end effector grabs the ball shaped segment of the root point, the boom position and rate data could be transmitted to the shuttle via a free space RF or Laser data link. When the shuttle velocity is reduced to .03 m/sec (.1 fps), the end effector would "pull itself" to the root point to assist in mating it with the boom end connector.

A third approach is to use a laser ranging and tracking radar coupled with a laser free space data link to provide the shuttle with the necessary position and rate data relative to the shuttle. When the shuttle velocity was reduced to 0.03 m/sec (0.1 fps) the capture and arrest could be made with the boom as in the first approach above.



(a) About To Make Quick Capture

(b) After Capture, Speed Arrest And Then Connector Hook Up

FIGURE 16.
SCHEMATIC SHUTTLE CAPTURE QUICK GRASP END EFFECTOR

2.4.5 Component/Tool Tote Box

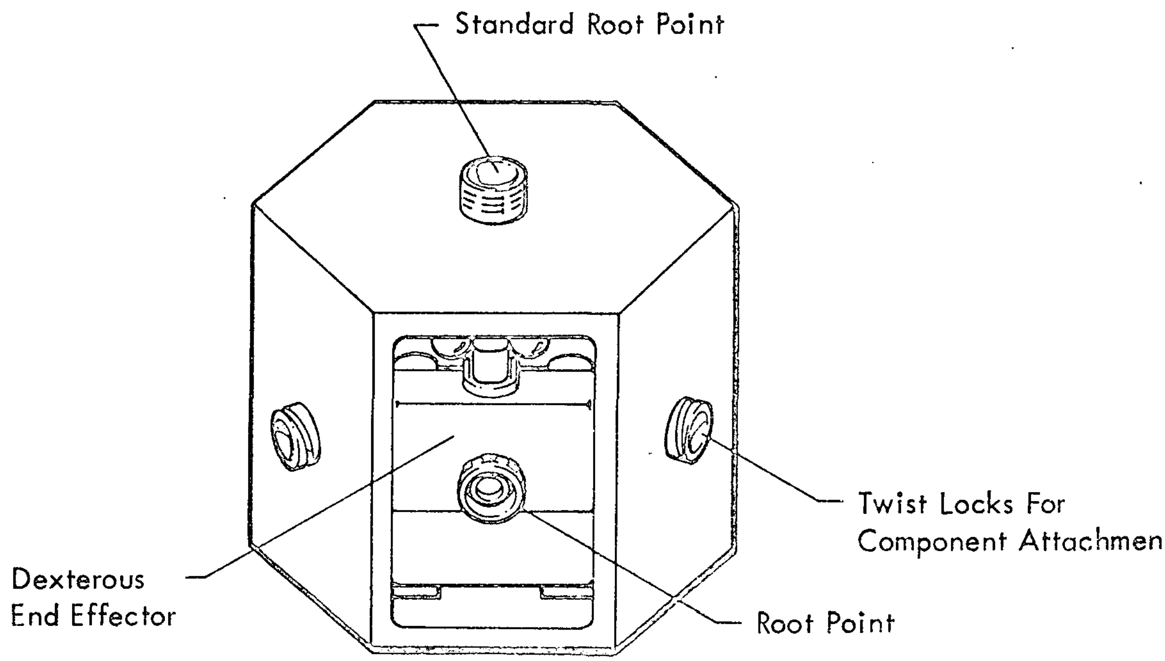
If the boom is to do other than transfer/berthing operations, (such as replaceing/repairing components on the station or perhaps even a satellite) a means for carrying and accessing such components and necessary tools is required. This can be accomplished with a tote box such as illustrated in Figure 17. The tote box itself is illustrated in Figure 17(a). In essence it is a modular extension of the boom which has storage bins and quick, twist lock connectors for attaching and carrying a variety of devices. A standard passive root point is on top and a standard active boom end connector is on the bottom of the box. To use the tote box, the free end at the boom is connected to the box root point and the box loaded with the parts and equipment required for a particular task. The boom can then walk end-over-end until the tote box end of the boom is connected to the desired working root point. The boom can then access or store parts on the box as shown in Figure 17(b) to accomplish the task.

2.4.6 Dexterous End Effector

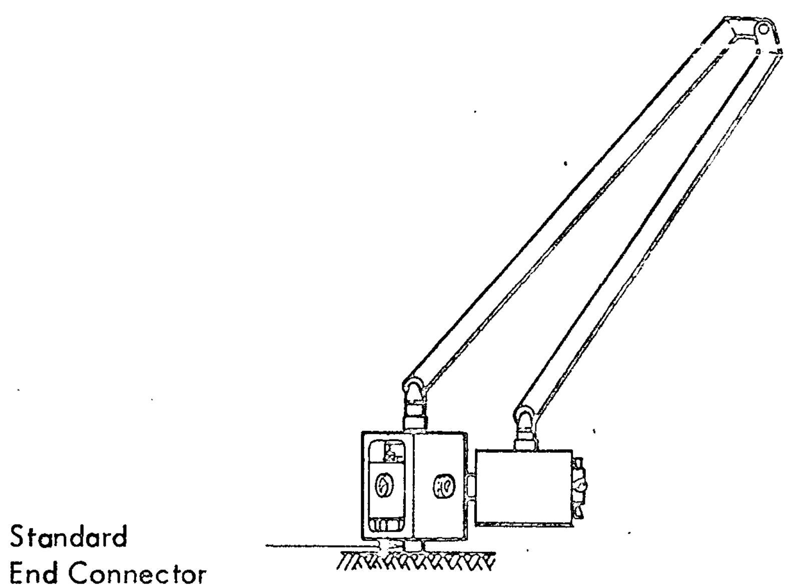
No attempt has been made to design a dexterous teleoperator end effector (TOEF) in this study; however, a schematic unit is illustrated in Figure 18. It incorporates the dual field, stereo-foveal/3 lamp camera and illumination assembly described in Section 2.3 "System Description". It is not likely that the boom would be steady enough for many tasks without some support of the tip at the work area. The two grapling arms shown on the TOEF are for that purpose. When they are used in combination with the boom and all are "locked up", the TOEF should be quite steady.

A small tool storage bin is indicated in the TOEF . For general purpose capability, a variety of "hand grips" and special tools would be carried in the bin. Some storage for small replacement parts would also be required.

The arms of the TOEF could be used to lock the TOEF to a work area while the boom is disconnected to bring up other hardware/equipment. The arms could also be used to hold the TOEF in the tote box as



a) Tote Box With Stowed Dexterous End Effector



b) Boom Attached To Tote Box Reaching For Propulsion Package

FIGURE 17.
SCHEMATIC OF TOTE BOX CONCEPT

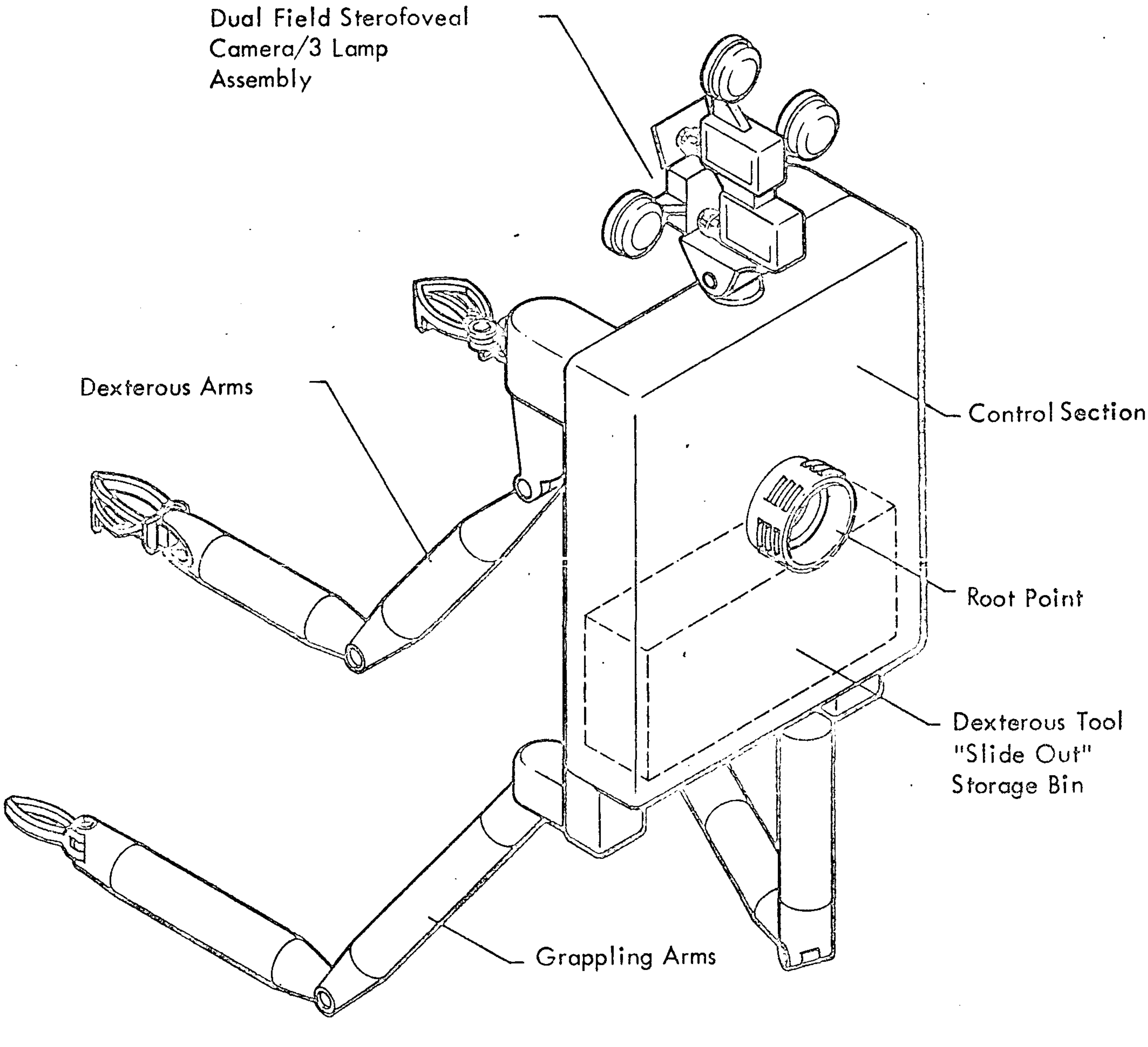


FIGURE 18.
SCHEMATIC DEXTEROUS END EFFECTOR

illustrated in Figure 17(a).

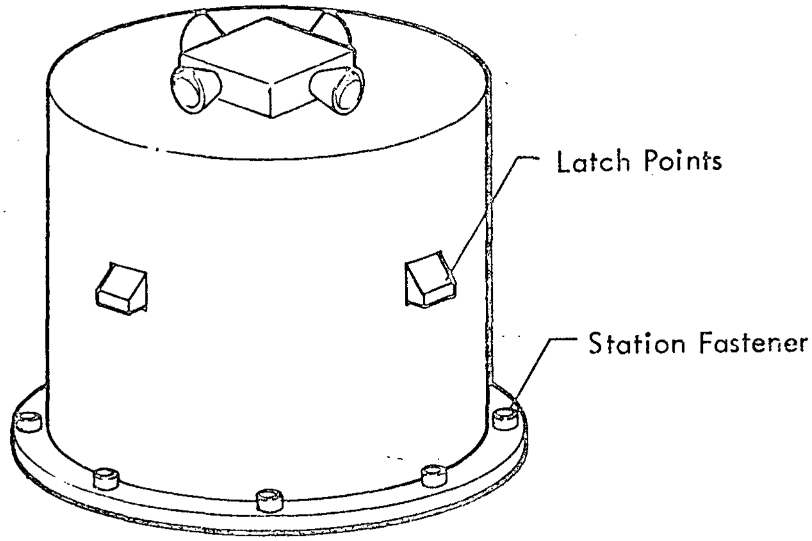
2.4.7 Propulsion Package Replacement

Propulsion packages (quadjet units with controller/actuation, etc.) will be placed at the ends of several of the space station side modules and they will require periodic maintenance/replacement. Details of the propulsion package configuration, its utility requirements, connectors, etc., are not known at this time. However, two approaches to propulsion package replacement can be considered; (1) the use of a special end effector which can cradle (hold) the package and actuate the fasteners and (2) the use of a TOEF in a "man like" replacement mode. The second approach would require a variety of tools, parts holder, fixtures, etc. The first approach, therefore, seems a more likely candidate.

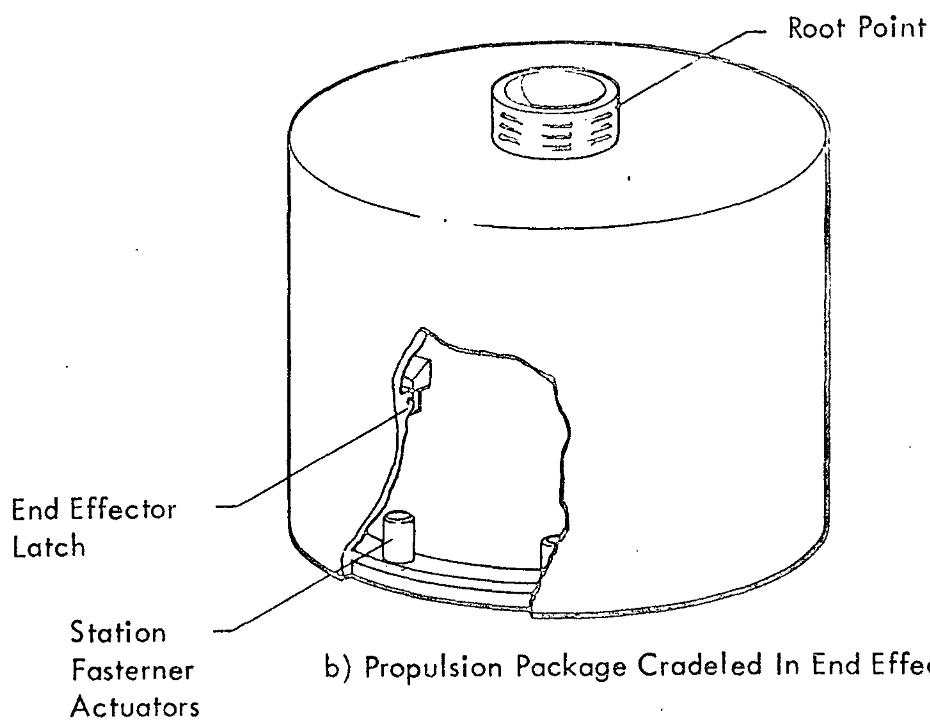
Such a special end effector is illustrated schematically in Figure 19. The propulsion package would incorporate passive alignment guides and catches such that the end effector could be slipped over the top, brought into proper alignment and latched to the unit. Individual actuators on the end effector would engage in the fasteners on the propulsion package. The entire unit would then be mated to the propulsion package mounting point, and the fasteners actuated. The mounting point/propulsion package would require compatible utility connectors and alignment guides (visual and/or otherwise) to facilitate attachment. Removal of a propulsion package would be done in reverse order. The above approach is analogous to the LST module replacement described

2.4.8 Manipulator/Space Systems Design Philosophy

It is evident that a manipulator system can greatly increase the capability and cost effectiveness of future space systems. It can also increase their reliability and safety by providing an on site, adaptive means of dealing with the unexpected. However, in order to realize the maximum benefits that can be achieved with a space manipulator system and in some cases, to even make tasks tractable, it is a <u>must</u> to design the entire space system with manipulator use in mind. Thus, locking devices, fittings and components to be handled should be designed for manipulator handling at their inception. Assembly replacement and berthing, deployment and all other operations should be designed for remote handling in a zero-g environment with special/general purpose end effectors and other auxiliary devices rather than try to adapt special devices to man's normal, earth-bound way of doing things.



a) Propulsion Package



b) Propulsion Package Cradeled In End Effector

FIGURE 19.
SCHEMATIC PROPULSION PACKAGE END EFFECTOR

2.5 Reliability/Maintainability

The selected manipulator system has been designed throughout with reliability/maintainability in mind. The main boom is the most critical element of the system since it is directly exposed to the space environment and physically engages with objects to be manipulated.

For shuttle applications high reliability can readily be achieved because frequent ground based inspection and maintenance procedures can be implemented (the manipulator system can be checked and serviced for each shuttle flight). Since the shuttle will be operational and used for satellite service prior to deployment of a space station, an opportunity exists for developing a reliability base and verifying or upgrading the manipulator to space station requirements.

The overall walking boom concept is particularly attractive for achievement of minimal down time and easy maintainability for the space station application. Since the boom is easily transferred between the shuttle and station, it can be systematically rotated with a refurbished/re-qualified boom on each normal shuttle/station logistics trip. (Even if made of aluminum, the boom only weighs ~281Kg [620 lb] so that it does not represent an appreciable payload sacrifice). The boom end cluster assemblies would be expected to require more maintenance than the elbow. If required, the entire elbow can be hermetically sealed with a metal bellows because it is a pivot joint where as the end clusters have roll joints which would require a pliable (and perhaps elastic) boot subject to periodic replacement. If the required maintenance interval was more frequent than normal shuttle visits, the end clusters could be serviced/replaced in orbit by inserting the wrist into an airlock through a special bulkhead designed to mechanically lock and seal with boom. A bulkhead seal within the boom arm would make shirt sleeve maintenance possible. The walking boom feature would also allow each end of the boom to be serviced in this manner.

The boom also has the following additional design features intended to maximize reliability.

(1) Non-back drivable actuation - If an actuator drive system fails completely, the joint is not free to rotate so that the boom can still be operated.

(2) Dual actuator drive system - Completely redundant actuator drive motors/power amplifiers/controllers have been used so that the joint can still operate at half maximum load if one drive unit fails. If the amplifier or motor fails open, the other motor continues. If the motor or amplifier fails short, the fuse clears the load from the supply bus. When a drive unit fails, the clutch for that unit is opened so that it doesn't overload or stop the remaining drive unit.

(3) Replaceable Root Points - The root points are designed to be removable from the shuttle/station hard points so that they can be replaced in the event of wear or damage. Normally the root points would be replaced with the boom using a special end effector. If the boom failed, the root point could be removed (with the boom attached) by use of another (replacement) boom and special end effector or by EVA procedures. An alternate is to cut or free the boom away explosively and later replace the root point.

(4) Joint Redundancy - The boom has 7 joints so that the same 6 DOF operations can still be performed if a joint fails. The dexterity of the boom after a joint failure depends on which joint failed. Failure of the "shoulder" index joint may cause only minor performance degradations whereas failure of the elbow would make the boom nearly useless.

(5) Redundant Wire Connectors - Dual pins are used for each wire pass through to minimize the possibility of a pin connector open circuit.

(6) Data Bus - The boom can be operated in emergencies (computer failure) by a joint at a time rate mode through the inner control loop. The digital data bus is still required, but multiple addresses at each joint can be provided to enhance reliability.

The control station sees only the space station or shuttle interior environment. Standard space electronic practices can be used to achieve a reliable system. The electronics can be modular for easy replacement. If there are several computers available on the shuttle or station, they might be used if the manipulator computer fails the emergency operating mode (computer failure is described above). When the station and shuttle are operating together, the control station in either one may be used to operate the manipulator in the event of failure on the other control station. This could be accomplished by attaching the boom on the vehicle with the operating control station or by interconnecting the operational control station to the data bus of the vehicle with the failed station (the interconnection would be achieved through the station/shuttle berthing port).

The manipulator visual system has a high degree of redundancy by use of multiple cameras and lights, fail safe automatic camera features and a separate dedicated viewing boom. Direct viewing aids are also used as a backup. In emergencies the viewing boom could be used for certain tasks.

The manipulator system by its very nature can improve the reliability/maintainability of the station or shuttle if it includes dexterous and other special end effectors and auxiliary devices. Thus inspection, maintenance and repair of the primary systems and payloads can be accomplished. Furthermore the properly equipped manipulator would have a degree of self repair capability.

2.6 Safety

The most important aspect as far as safety is concerned on the manipulator system is the safety of the space personnel. No manipulator system failure should jeopardize their safety or create a hazardous situation in space. As with any vehicle or equipment, operational safety can only be achieved with proper operating procedures. For example, approaching the boom end while it is extended straight out could result in penetration of a vehicle hull. Fly-by or capture operations should always be done on a non-collision course with the boom held in a flexed configuration.

Several important safety features have been designed into the manipulator system. The capabilities offered by the computer are particularly important. Except in emergencies (computer failure), the computer always interfaces between the operator and the boom. The computer has stored in its memory a complete updated representation of the shuttle and/or space station configuration. All existing and projected future positions of the boom are examined for potential collisions with an obstacle. The computer will avoid any such potential collision by programming around the obstacle or stopping the boom. The computer also monitors all joint speeds, torques, etc., to assure that the joints are always operated within their capability and that the velocity of the object being manipulated is never so great that it cannot be stopped prior to collision. The computer controlled operations can always be monitored by the operator and if required, the operator can stop the boom in the event of a computer malfunction or failure.

The slip clutch feature of the boom joints assures that the boom cannot be inadvertantly overstressed. The slip clutches also serve as effective energy absorption devices to provide additional safety in event of, say, a shuttle berthing malfunction. (It is planned to have the shuttle ACS reduce the shuttle/station closure velocity after capture. If the shuttle ACS should malfunction, the boom clutches provide a means of decelerating the shuttle and dissipating its energy without damage to the boom).

Location of the manipulator root points on station or shuttle hard points, other than berthing ports, reduces the possibility that the manipulator can interfere with crew egress. If it should happen that the manipulator fails across an emergency exit port, it can be pushed out of the way by causing the clutches to slip.

It is quite possible that with the manipulator, the total safety of the space station system will be increased. One can visualize,in an emergency evacuation situation,where the crew cannot get to the shuttle through the normal exit docking ports . In this case, the manipulator might be able tc move a module filled with the crew from the space station or from a disabled shuttle down into the rescue shuttle bay. Another mode of operation would be where the crew has to go EVA. In this case, they would be able to climb down the boom to the rescue shuttle cargo area.

In order to have a safe manipulator, it is important that it is not damaged during its operation. To assure this, the materials are stressed to levels well below their yell point or even endurance limits. Safety factors of 8 to 16 are used in the main boom. The slip clutches as described above and the redundant motors and electronics also enhance the overall manipulator safety by increasing its operational reliability.

2.7 Technology Requirements and Problem Areas

2.7.1 Technology Requirements

The basic manipulator system is based on state-of-the-art technology. No concepts are based on future breakthroughs although there is some uncertainty about the achievable, maintenance-free, in orbit, life time of the actuator joints (without complete hermetic seals) and the boom end connectors. Development of satisfactory joints and connectors present no servicing problem for shuttle mounted manipulators, since ground maintenance can be employed. If, for the space station manipulator, long, in-orbit life (years) proves to be difficult to achieve, all pivot joints can be hermetically sealed with bellows and an airlock maintenance procedure can be established for the wrist/shoulder roll joints and end connector assemblies. An alternative is to rotate refurbished booms as a part of the periodic space station/shuttle logistics program. Many of the required components including color TV cameras, telemetry and data processing systems, have already been used in space. The reference structural materials technology is well established and space qualified lubricants are available. However, engineering development and system engineering and integration supported by extensive testing and simulation studies is required to properly merge the components and subsystems together into a viable, effective manipulator system.

Control and use of a large, light weight "flexible" boom (which cannot lift its own weight in a 1 g field) is beyond current manipulator experience. Detailed analysis of boom dynamics and full scale zero-g simulation studies will be required to develop suitable control damping techniques.

The capability to accomplish a broad spectrum of tasks ranging from simple bulk cargo handling to remote precise dexterous repair/maintenance is required of the present manipulator system. This requirement places overall demands on the integrated man/machine interface beyond that of any existing manipulator system - although the feasibility of most of the important control and feed back features have been successfully demonstrated on an individual basis. These demonstrations include the following:

(1) A black and white, head-aimed, monocular, foveal TV system (John Chatten, while at Control Data Corporation)

(2) A black and white/color, head-aimed, single-field, sequential stereoscopic TV system (Lyman Van Buskirk of the U. S. Naval Weapons Center)

(3) A joy stick positioned, 2 camera, split image, superimposed stereo foveal/monocular peripheral black and white TV system (MBA - see Volume IV "Simulation Studies")

(4) A black and white, split image, single camera steroscopic TV system with automatic convergence control (James Jones, NASA AMES)

(5) Remote threading of a household needle by MBA using NAT and a joystick controlled single camera, split image stereoscopic, black and white TV camera in conjunction with a single, wide angle, monocular TV camera.

(6) Computer controlled end point rate control of a mechanical arm (MIT)

(7) Scale model/computer, time delayed, motion smoothed, expanded time scale, supervisory control of NAT (MBA - see Volume IV "Simulation Control")

Thus, development of the man/machine interface involves integration of the above techniques into a well laid out, effective control station. Simulation studies will be required to fully develop the controls and displays and to establish the required levels of precision, resolution and depth cues necessary to accomplish the selected mission tasks.

The "walking" boom feature of the selected manipulator system is a powerful technique which greatly expands the multi-purpose capability of the system by providing high mobility, interchangeability and maintainability. It's success depends on the ability to reliably make and break the root point, electro-mechanical connection under space environmental conditions. There is a large variety of space qualified electrical connectors, including multiple single wire and coax assemblies, but it appears that no connector has been specifically designed for repetitive connect/disconnect use while in space. It is believed, however, that a suitable connector can be developed in a straight forward engineering fashion and that no material break throughs are required.

The astromast type viewing boom has already been developed in prototype form for other space applications (for example, deployment of solar panels in a space station or large satellite). It is only necessary to configure it for the specific viewing requirements of the station and shuttle. This will include incorporation of two additional shoulder DOF's, three distal end camera orientor DOF's, power and control leads to operate cameras, lights and actuators and, finally, root points and connectors on the shoulder assembly to enable movement about and attachment on the station/shuttle, respectively.

2.7.2 Problem Areas

The manipulator system can be built with existing technology for shuttle applications. Some technology development may be required for the space station application depending on the experience with the shuttle system and on the maintenance approach adopted for the space station system. Specific problem areas identified as a result of this study are summarized below.

2.7.2.1 Manipulator Boom

(1) Structural Material. Significant improvements in weight and performance can be achieved if beryllium (or beryllium alloys) can be used. Studies should be initiated to investigate the crack sensitivity, fatigue limits, fabricability and availability of candidate beryllium alloys.

(2) Actuators. Actuators are the key to successful reliable and safe boom performance. Detailed design, development and testing are required to demonstrate that sucessful operation in a hand space environment under maximum simulated boom load conditions is required.

(3) End Connector/Root Points. The success of any space manipulator system is dependent on having an electrical connector which can operate (connect/disconnect) reliably for thousands of cycles in a hard space environment. Detailed design, development and testing of a suitable connector to demonstrate that successful operation in space can be achieved is required.

2.7.2.2 Man-Machine Interface

Development problems arising from the design and analysis of the present man/machine control concept include:

(1) Man/Computer Communication

Develop an indexing system and special-purpose "language" to permit efficient transmittal of desired boom movements to the computer.

2 (4)

(2) Interpretor Software

Develop and implement the computer programs which will interpret the symbolic movement commands, and generate the required control inputs to the boom mechanism.

(3) Model Controller

Using the experience of the present simulation, develop a full 7-degree-of-freedom model controller isomorphic to the boom, natural to use, and meeting the design requirements of the console. Develop an associated system for specifying at the controller the points on the space station between which, or around which, the manipulator must be guided.

(4) Trajectory Storage and Optimization

Extend the techniques of the simulation program to encompass the full manipulator degrees-of-freedom. Incorporate collision-avoidance and optimum path criteria in the trajectory "smoothing" routines.

(5) Mating and Berthing

Develop the control display system to optimize mating and berthing of the manipulator end-effector and module loads. Particular attention must be paid to (a) the master controller, (b) alignment guides, and (c) display/control compatibility. A series of simulations will be required.

(6) End-Point Control

Develop and implement the computer programs which will generate movements of the manipulator end cluster with respect to the display coordinate system. Incorporate routines to handle dynamic restrictions on mating and release.

(7) Time-Line Analyses

Perform detailed time-line analyses of the operator's task during execution of planned manipulator operations to provide initial performance estimates and uncover potential trouble spots.

(8) Console Design

Provide a full-scale console mock-up as a vehicle for final optimization of the functional areas, detailed specification of display/ control components, and more reliable size and weight estimates.

2.7.2.3 Visual System

The viewing system has been designed to make maximum use of available equipment and techniques. However, development will be needed tc adapt a number of component subsystems and techniques to be used, as well as to integrate them into the viewing system.

(1) Zoom Lenses. Currently available remote controlled zoom lenses are not designed to focus to distances smaller than 4 feet. The stereo foveal cameras on the dexterous manipulator will have to work at shorter distances. At the moment, there is work in progress on "macro-zoom" lenses. Paillard-Bolex is making this type of lens for an 8 mm camera without remote control. Special zoom lenses will have to be designed for both the foveal and the peripheral field ranges since these lenses require focal length ranges not available in present models. The peripheral lens must parallel the focal length range of the foveal lens, multiplied by the field ratio. Thus, for a 50-500 mm foveal lens, a field ratio of 5 will call for a 10-100 mm in the peripheral lens. Also, a zoom coupling device must be developed to keep the field ratio constant while zooming the two lenses.

(2) Automatic Focus and Stereo Convergence. The technique proposed for automatic focus is still in the experimental stage; however, Nikon is marketing a device using a similar principle. Further development of auto focusing is required. It will be a straight-forward problem to couple the stereo convergence control to the automatic focus device, to have the stereoscopic fields converging at the viewed object.

(3) Parallax Stereogram TV Display. This type of display depends on maintaining scan line registration within the limits of the lens array field. Various techniques of doing this have been perfected during the development of color television. A technique for monitoring line registration similar to the one described in this report was developed by John Chatten at Philco in the fifties and its feasibility was proven. Work is needed to integrate the whole display. Good mechanical stability and precision are also needed.

(4) Camera Controls. There is insufficient data presently available to select the preferred camera orientation control method. Eye control is attractive and the techniques for determining eye vector position exist. Design and human factor simulation studies are required to establish acceptable eye position/scan sequences and to investigate alternate control concepts.

(5) Illumination. Simulation studies are required to define acceptable lighting and contrast levels. Surface color and finish should also be investigated as a means to assist illuminating and featuring the work area.

2.7.2.4 Control System

From an overall view point design of the boom electronic control system appears straight-forward. However, the effects of the desired non-back-driveability of the actuators requires investigation. Development of suitable means to provide dynamic electronic damping of boom oscillation is required.

2.7.2.5 Auxiliary Viewing Boom

The auxiliary viewing boom is based on the astromast already developed in prototype form. The effects of shuttle/station dynamic movements and vibration characteristics and general performance (vibrations, oscillations) of the auxiliary viewing boom as a camera platform must be investigated.

2.7.2.6 End Effectors

Preliminary design studies of manipulator end effector applications should be accomplished to establish necessary end effector requirements and design characteristics.

2.8 Growth Potential

The selected manipulator system offers significant growth potential that can be phased in with the shuttle, satellite and space station development and operational programs. Shuttle based manipulator operations will be the first to occur and these will progress from simple inert satellite deployment and retrieval (the meteoroid module) to modular resupply and servicing of a complex station-keeping satellite (the Large Space Telescope). Direct viewing in conjunction with a modest (single field monocular TV system may be acceptable for meteoroid module deployment and retrieval and for LST servicing. Thus the manipulator system can begin operation in a fairly simple form and be upgraded in complexity and capability as task requirements dictate.

In order to accomplish such growth it is imperative that the manipulator system be designed with growth potential in mind. The data processing and transmission system must have sufficient capacity for handling increased command, monitoring and video functions. The control console should be laid out to accommodate upgraded viewing system (displays) and manipulator controllers. The root points should be designed with a large strength margin to handle stronger and stiffer booms as they are developed. An adequate array of root points should be installed on the shuttle satellites and station modules to allow flexible, mobile use of the manipulator.

A workable manipulator can readily be built using aluminum alloys as the primary structural material. It is also very probable that a satisfactory beryllium, or beryllium alloy, boom can be built today to provide greater stiffness and comparable tip force capability for approximately 1/2 to 3/4 the weight of an aluminum boom. The utility of beryllium is limited by its generally poor fatigue/crack sensitivity. However, by proper design and fabrication, and use of low stress levels, (the boom is deflection limited rather than stress limited) a beryllium boom could be desirable. Certainly, as the state-of-the-art in beryllium and in lightweight, high strength composite materials is advanced, the manipulator boom capability can be upgraded by employing them.

The present boom design was limited by NASA MSC to a 22.8 cm (9") diameter in order to facilitate storing the boom in the shuttle cargo bay along with payload modules. A more nearly optimum diameter is 38.1 cm (15") which, for the same nominal weight, the boom deflection can be reduced by 64% for the same tip force and the boom tip force can be increased by 67% for the same wall stress. Therefore, from the manipulator point of view, it is desirable to have a dorsal fin storage volume on the shuttle to accommodate a 15" diameter boom. If such a fin is built into the shuttle at a later time, the boom could then be increased in diameter to provide greater boom stiffness/tip force capability.

2.9 Development Resource Requirements

2.9.1 Development Program Model

Only the basic manipulator system is considered; i.e., no end effectors or other auxiliary devices are included (see Background above). Also no ground support equipment or shuttle flight test support is included. It is assumed that full scale zero-g simulation facilities will be built by NASA MSC and made available to the program at no cost. No attempt has been made to define the zero-g test facility requirements since such facilities were beyond the scope of the present study.

The equivalent of five manipulators systems are fabricated during the assumed program. These consist of one each of the following:

(1) Engineering Model

A functional system built up in an iterative manner to develop for the first time all of the manipulator system components and subsystems and to work them together as a complete system. An attempt will be made to configure all components as if they were to be flight hardware, however, many changes, to meet flight hardware requirements, will be required.

(2) Mock Up

A partially functional system in which all components are configured externally to meet the flight hardware envelope, interface and mass property requirements. Engineering model or even non-functional internal components may be used as long as such components reflect proper power, load, and control requirements to the shuttle mock up system.

(3) Prototype

The first flight hardware configured manipulator system. The prototype represents an integration of the engineering model and mock up systems. Iterative changes will be made until the complete system is configured as required for space flight use. The final configuration will be the system Final Design subject only to change as required by the qualification test program. Sufficient developmental testing will have been accomplished to provide high confidence of passing the qualification tests with few or no changes required.

(4) Qualification Unit

The first system built to final manufacturing release drawings and specifications using hard tooling. It will be subject to the complete range of environmental conditioning and functional performance tests required to qualify the system as flight ready. Because of its size and because it cannot lift its own weight in a 1-g environment it is anticipated that much of the qualification testing will be done at the component and subsystem level.

(5) Flight Unit

A fully qualified system made using final manufacturing release drawings and specifications and hard tooling. This system will incorporate any changes required and proven to meet all of the qualification test requirements. It will be subject to flight acceptance tests only and after successful completion and certification will be delivered for the shuttle/manipulator space flight test program.

The following shuttle development program milestones were assumed:

(1) Shuttle mockup available for mockup hardware integration studies on the 18th month.

(2) Shuttle prototype available for hardware integration and check out on the 24th month.

(3) Manipulator Qualification Unit delivery required on the 38th month.

(4) Manipulator Flight Unit delivery required on the 48th month.

The development program was broken down into the following 7 tasts.

(1) Program Management

This task extends through the life of the program and provides overall technical and administrative management, cost and schedule control and top level program management and direction for configuration management, reliability, quality assurance and safety.

(2) Specifications and Requirements

This task generates detailed specifications and requirements for the complete manipulator system and its components and subsystems. Itwill include shuttle/manipulator interface requirements, functional requirements, performance requirements and reliability and safety requirements.

(3) Design Trade Off Studies

This task consists of detailed analytical and experimental trade off studies required to establish a near optimum initial design. Additionally some trade off studies will be required to establish the system requirements and specifications.

(4) Engineering Design

This task consists of all the engineering analysis, and design and all of the developmental hardware fabrication required for development of the manipulator system up through the prototype unit. It also includes continuing engineering design support for the qualification test unit. Hardware testing and simulation efforts are accomplished in Tasks 5 and 6 respectively.

(5) Simulation Studies

This task consists of experimental simulation studies required to develop the man-machine interface, the boom control system and suitable space task operational procedures. The man-machine interface studies will establish illumination level and operator TV display requirements necessary to accomplish planned space operations.

(6) Testing this task consists of all the hardware testing required in support of engineering development, system qualification and system flight acceptance. It also includes design and fabrication of small special purpose test fixtures and assemblies but does not include design and fabrication of major test facilities such as thermal vacuum chamber etc. Such facilities and environmental conditioning facilities will be leased, rented or subcontracted for.

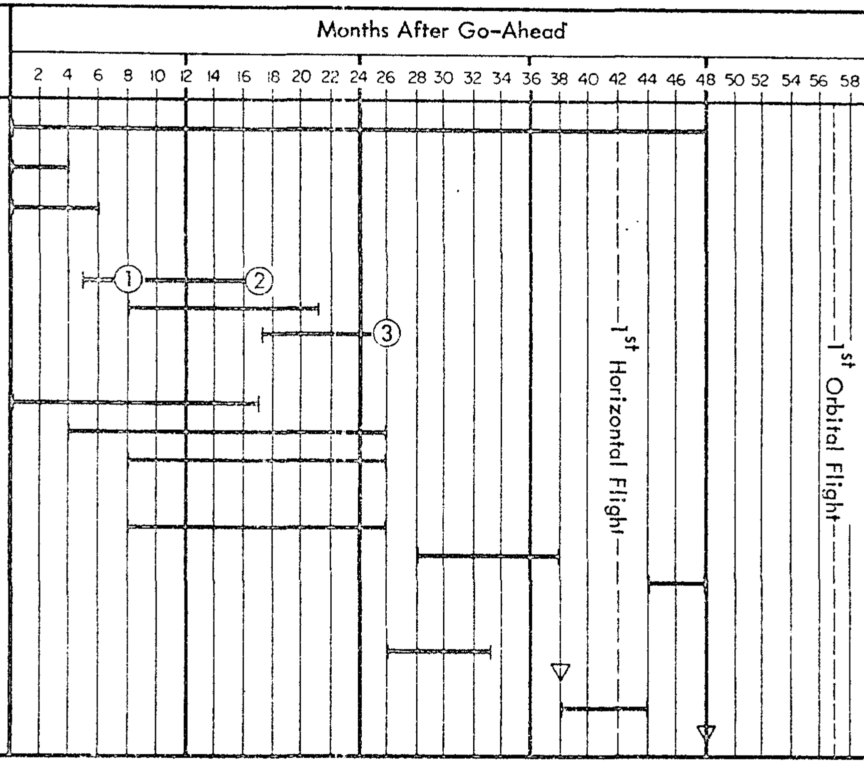
(7) Deliverable Hardware

This task consists only of fabrication, assembly, check out, support engineering and documentation required for the deliverable units (the qualification and flight test systems).

2.9.2 <u>Schedule and Resource Requirements</u>

The estimated schedule and resource requirements based on the model described above are summarized in Figure 20. The manpower estimate includes all categories such as engineering, drafting, technicians, shop, clerical and inspection.

Task	Manpower MM	Cost (In Thousands) Labor	Cost (In Thousands) Material
1.0 Prog. Management	240	1040	
2.0 Specifications & Rqmt's	41	128	
3.0 Design Trade off Analysis	280	840	
4.0 Engineering Design			
Engineering Model	915	2750	2510
Mock Up	253	760	440
Prototype	784	2350	1960
5.0 Simulation Studies			
Man-Machine Interface	142	408	60
Control/Dynamics	120	360	50
Task Development	50	150	20
6.0 Testing			
Development	84	252	50
Qualification	120	390	75
Flight Accept.	72	216	50
7.0 Deliv. Hardware			
Qual. Unit Fab.	225	674	590
Qual. Unit Deliv.	225	674	590
Flight Unit Fab.			
Flight Unit Deliv.			
Sub Totals	3551	10992	6395
Grand Total		17387 ± 25%	



① Preliminary Design Review
② Critical Design Review
③ Final Design Review

FIGURE 1.
ESTIMATED DEVELOPMENT PROGRAM SCHEDULE AND RESOURCE REQUIREMENTS

3.0 CONCLUSIONS

The basic, multipurpose manipulator system preliminary design established in this study consists of a single 7 DOF walking boom (without end effector), and internal control station, and a remote visual system including multiple cameras, lights and dedicated viewing boom. The conslusions which can be drawn regarding this system are as follows:

(1) The walking boom feature offers complete interchangeability between the shuttle and space station. In the basic configuration, the system can accomplish space station assembly, cargo module transfer, shuttle berthing and deployment of simple satellites.

(2) The addition, as required to the basic system, of special and general purpose end effectors plus auxiliary equipment (automatic scaffolding, special purpose booms or even a second standard manipulator boom) will provide a powerful general multipurpose system for a broad range of space tasks as including inspection, maintenance, repair, satellite assembly/erection, satellite retrieval and servicing, and astronaut rescues.

(3) The potential general multi-purpose capability of the manipulator system derives from the fact that it is an extension of mans' own adaptative, dexterous capability. The use of such a manipulator in space will improve the overall capability, reliability and safety of the space systems on which it is used. The ease and scope of the tasks which it can accomplish will be greatly increased by optimally designing space systems so that they can be serviced and maintained with a manipulator.

(4) Development of the manipulator system can be phased from the initial basic concept to a complete sophisticated array of end effectors and auxiliary devices as needs dictate and as operational experience and reliability data are accumulated. This type of development program phases very well with the planned shuttle, satellite and space station

development programs.

(5) For shuttle applications the manipulator system can be developed with existing technology and no break throughs are required. Some technology improvement may be required in the areas of dynamic seals and/or lubricants and space operational electrical connectors if long (10 years), in orbit, maintenance free life is required. These technology needs are not unique to the walking boom concept. A fixed boom has the same requirements even for the electrical connector since it too must be designed to have a space operable end effector, electrical connector to realize the potential of the manipulator system.

(6) The walking boom concept is particularly attractive for the space station application. It provides the necessary mobilityand a straight forward maintenance capability. Rather than attempt developing a 10 year maintenance free system, it may be better to develop it for planned periodic rotation as an integrated part of the overall space station/shuttle logistics program. Tne space station boom can be rotated with refurbished/requalified ground maintained booms on planned shuttle visits. With this approach, the station manipulator boom can be easily updated with new and improved configurations. Furthermore, the walking boom concept lends itself to in-orbit space station maintenance (if required between shuttle visits) by use of an air lock fitted with a special bulkhead.

(7) The selected manipulator system offers good growth potential. The boom can be built with aluminum and meet the 454 Kg (1000 lb) overall weight limit. The eventual use of a beryllium metal (or composite material) offers a two-fold reduction in boom weight with even greater stiffness and force capability. The selected manipulator boom has been restrained to a 22.9 cm (9") diameter to fit in the shuttle cargo bay along with full diameter cargo. If the shuttle

grows in size or is reconfigured to accommodate a more nearly optimum boom diameter of 38 cm (15"), the weight of the boom can be reduced and/or its force/deflection capability can be significantly improved.

(8) A ground based zero g space simulation facility will be required to develop the man machine interface, control techniques, operational procedures and to provide operator training. Air bearing, suspension type zero g facilities, neutral buoyancy facilities and artificial computer simulation facilities are all viable candidates for this purpose.

4.0 RECOMMENDATIONS

1) Establish the time schedule of desired manipulator system functional requirements. It is anticipated that initially, limited shuttle based, satellite related operations will be required followed by more complex satellite operations, followed finally by space station operations.

2) Re-evaluate shuttle stowage space limitations to possibly accommodate a 15" diameter boom.

3) Initiate engineering development of a manipulator system based on the preliminary design concepts developed in this study. This development program should be time phased to meet the requirements established in 1) above.

4) Initiate a preliminary design Phase A study of end effector including a dexterous anthropomorphic system based on current projected shuttle flights.

5) Investigate the crack sensitivity/fatigue characteristic fabricability and structural force availability of beryllium (and suitable alloys of beryllium) to establish if or when such metals should be used on the boom material and if so, what design data and/or technology improvements are required to implement such use.

APPENDIX 1.0

SHUTTLE AND SPACE STATION PARAMETERS

SPACE STATION AND SHUTTLE PARAMETERS

Mini 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 (Study Design Driver)

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

SHUTTLE AND SPACE STATION PARAMETERS
(Experiment Module)

Module Weight	29,500 Kilograms (65,000 Pounds)
Module Length	12 Meters (40 Feet)

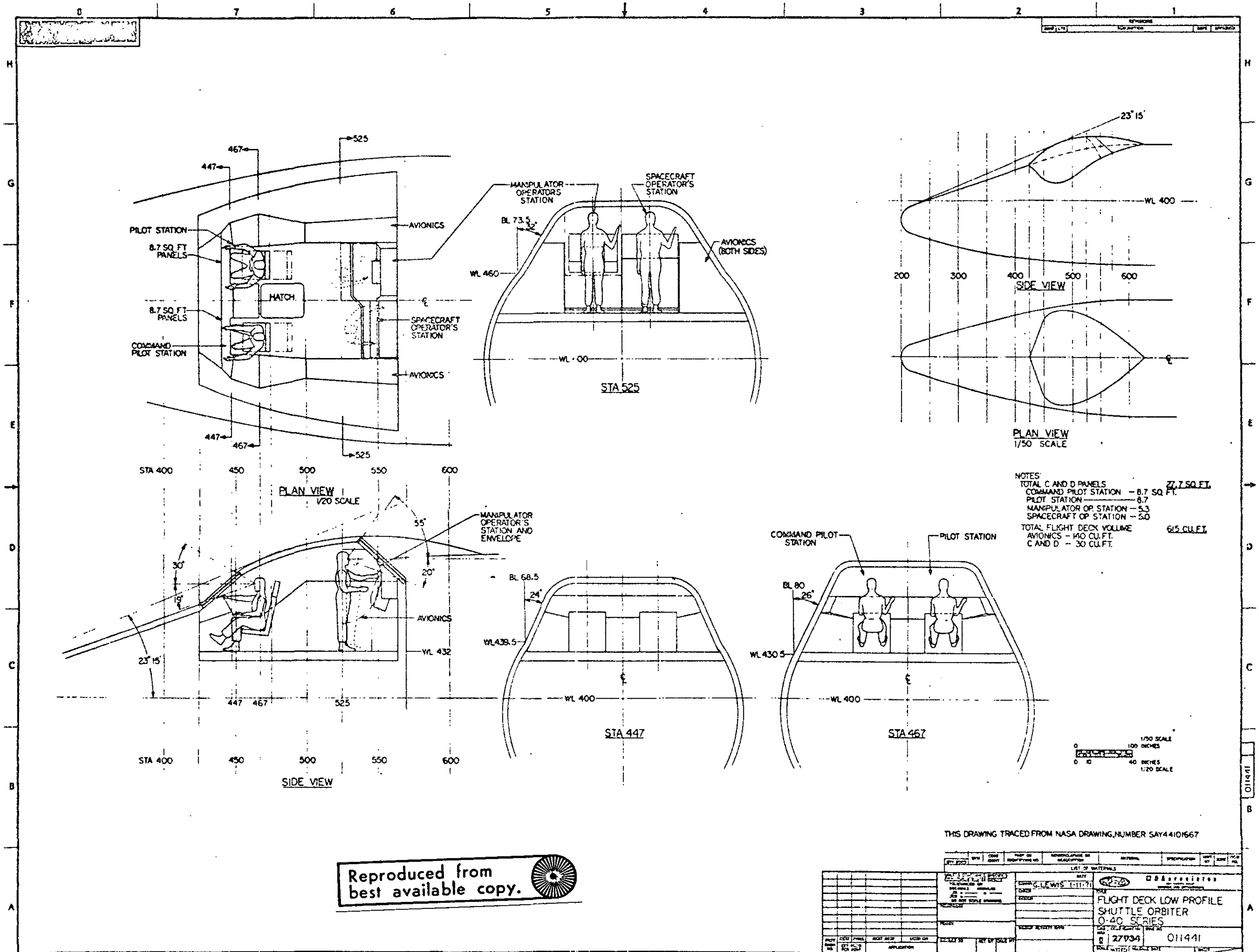


FIGURE 1-1

040A SHUTTLE CREW COMPARTMENT

3

0142-10062

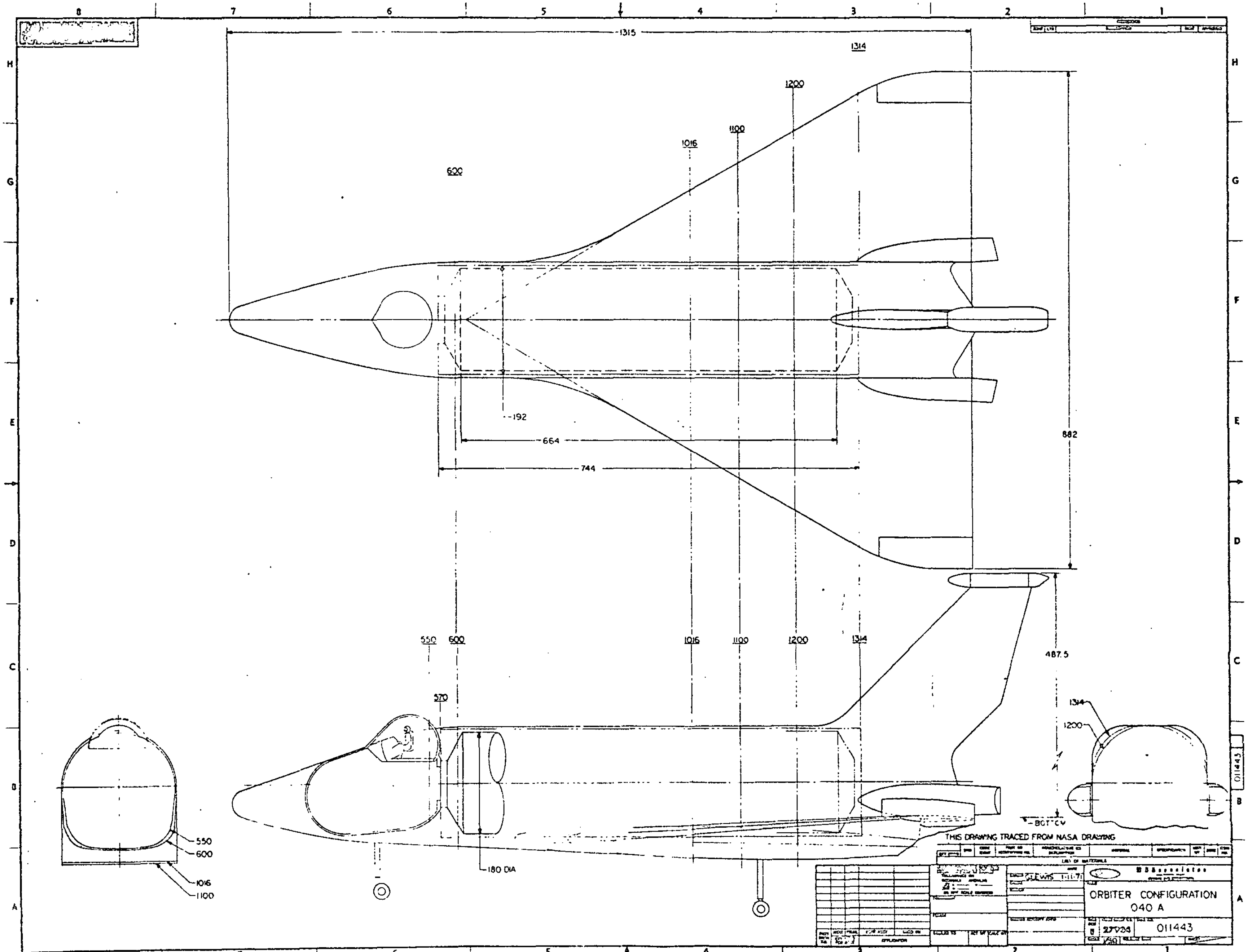


FIGURE 1-2
040A SHUTTLE OVERALL CONFIGURATION

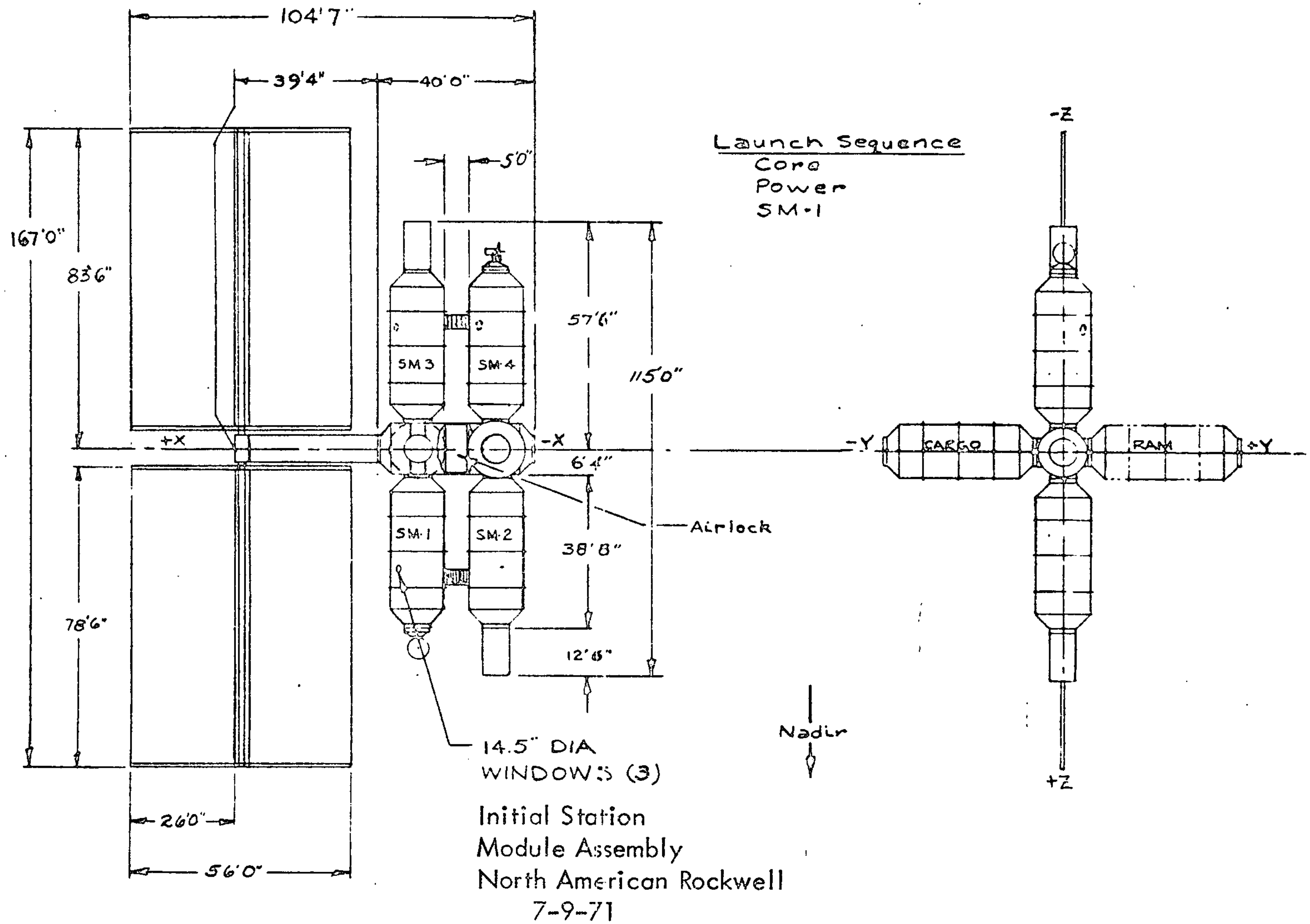


FIGURE 1-3
REFERENCE SPACE STATION CONFIGURATION (EARLY VERSION)

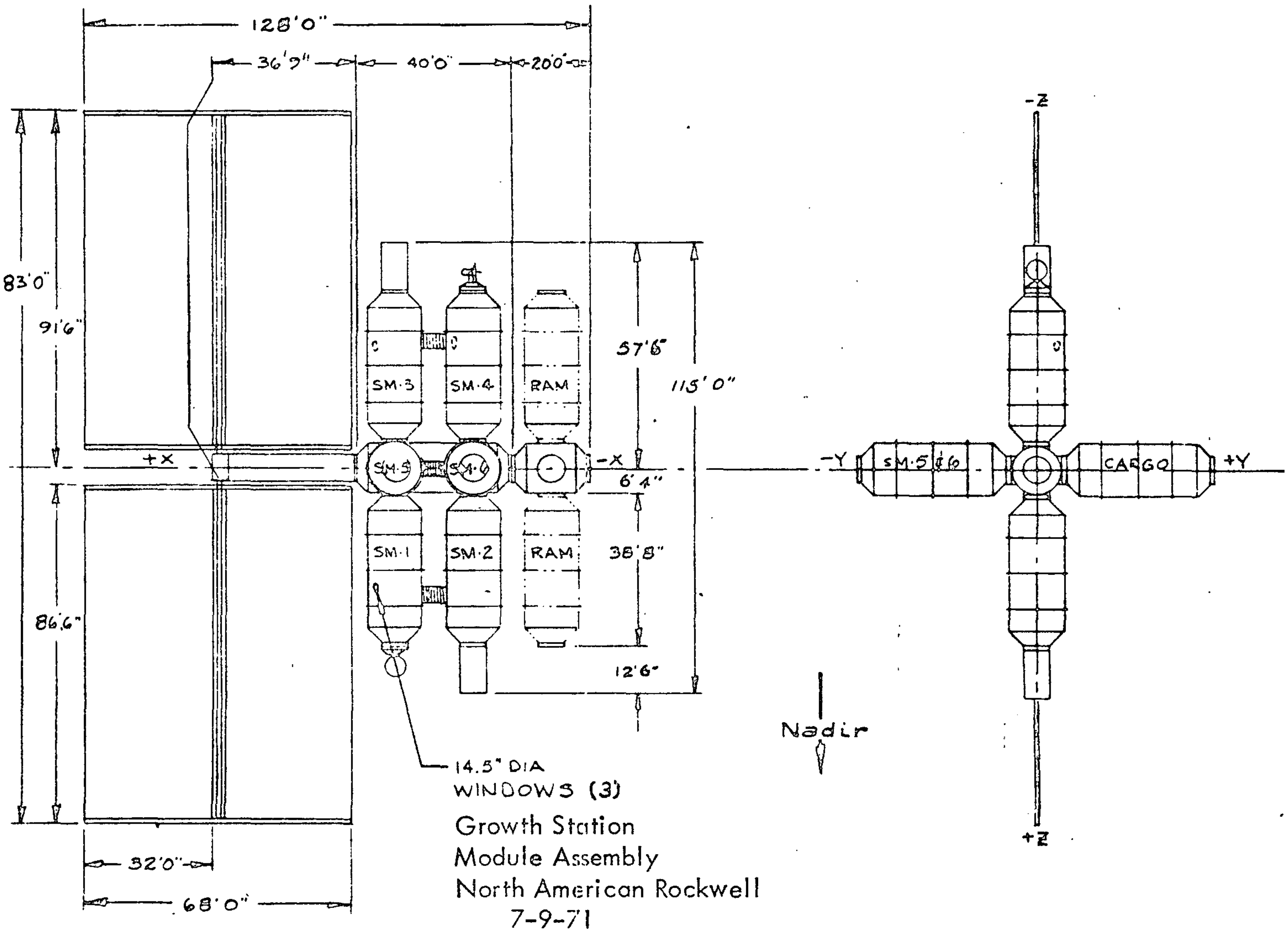


FIGURE 1-4
REFERENCE SPACE STATION CONFIGURATION (GROWTH VERSION)

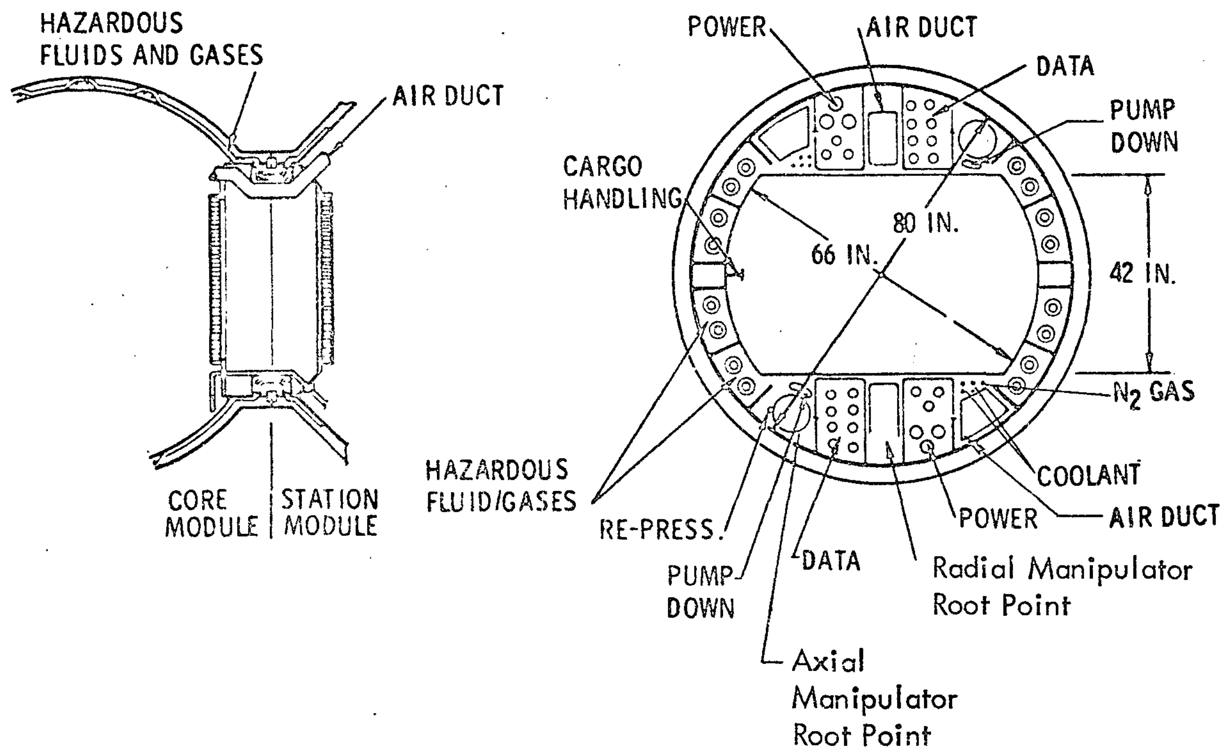


FIGURE 1-5
REFERENCE BERTHING PORT CONFIGURATION

APPENDIX 2.0

2.0 SYSTEM WEIGHT AND SIZE ANALYSIS

The design drivers which determine the manipulator system weight and tradeoff criteria can be categorized as follows:

Type	Item	Requirement	Source
1	Maximum allowable weight	≤ 454 Kg(1000)	Study Ground Rule
	Boom Diameter	≤ 22.9 cm(9")	Study Ground Rule
2	Dexterity Reach Mobility	As required to accomplish tasks	Study general requirements
3	Tip Force Level Deflection	As required to accomplish tasks	Study general requirements

The type 1 criteria are quantitative, easily understood and have an obvious physical impact on the manipulator system design. Type 2 are not as obvious but are readily resolved by kinematic studies of the required working envelopes and tasks. The type 3 criteria are not obvious and in fact have no firm judgement value; i.e., "The stronger and stiffer, the better it is". The approach used in this study was to establish a system configuration which best meets the Type 2 criteria with Type 1 criteria in mind and then to use best engineering judgement to select an "optimum" combination of tip force and tip deflection consistent with the Type 1 criteria. Once the overall system design approach was defined many of the component (subsystem) weights, which are invarient with tip force/deflection, could be defined. It then was a matter of trading off the remaining items (all associated with the boom) to select a final configuration. A summary of the overall manipulator system weight and a brief review of the weight trade off studys are given below. The reader is referred to the appropriate sections of Volume III (as noted below) for further detail on the trade offs.

2.1 System Weight Summary

2.1.1 The Overall System

The overall system weight is summarized in Table 2-1. The power system weight is a negligible part of the total weight since primary shuttle or station power is used. The control system weight is also negligible because the individual controlled power level (actuators) are low (136 watts maximum) and miniaturized solid state equipment is used. The control and power systems do not account for the wiring and miscellaneous switches, etc, required throughout the station or shuttle; however, since the boom is 18.3 m (60') long and the total power and control system weight (including amplifiers, encoders, decoders, etc.) is only 5 Kg (11 lbs), the weight impact of the wiring on the shuttle and station will be negligible.

2.1.2 Control Console

The control console weight summary is given in Table 2-2. The weight alloted in Table 2-1 is slightly larger to allow for contingencys.

2.1.3 Auxiliary Viewing Boom

The auxiliary viewing boom weight summary is given in Table 2-3. Note that it includes the TV and illumination light assembly.

2.1.4 Root Points

The study ground rules do not charge the manipulator system with weight of the root point arrays on the station, shuttle, cargo module, etc. The root point is estimated to weigh 1.7 Kg (3.75 lbs). This does not include the weight expenditure for the hard point to which it is attached or the wiring required to service it. If it is assumed about 10m ($\sim$30') of wiring carrier is required for each root point then, exclusive of the hard point structure, the weight expenditure per root can be taken as $\approx$3 Kg (6.6 lbs) each.

2.2 Weight Trade Off Analysis

To first order, only the boom weight varies as tip force and deflection are varied. The boom weight, material, tip force and deflection trade off studies for the selected design are described in Volume III "Weight and Deflection Trade Offs". Results of the material trade off studies are

TABLE 2.1

BASIC MANIPULATOR SYSTEM WEIGHT SUMMARY*

	(Kg)		(lbs)	
Component	Component	Subtotals	Component	Subtotals
Dedicated Viewing Boom (with TV Camera & Lights)	---	53	---	117
Main Boom	---	281	---	620
Actuators (7)	105		231	
Clutches (7)	16		35	
End Connectors (2)	18		39	
Tubing	142		315	
Power System (1)	---	2.3	---	5
Control System (1)	---	2.7	---	6
TV System (2)	---	37	---	82
Control Console	---	45	---	100
TOTAL		421		930

* Based on Al as the primary boom reference structural material. It is estimated that the boom weight could be reduced to ≤ 141 Kg (310 lbs) by use of Be

TABLE 2-2

CONTROL CONSOLE WEIGHT ESTIMATES

Units	Description	Total Wt	Total Wt
1	Stereo/Foveal TV Monitor	6.8 kg	15 lbs.
2	Auxiliary TV Monitor	4.5	10
1	Terminal CRT Monitor	2.3	5
1	Rear-Lighted Graphic Panel	0.9	2
1	Computer Keyboard	0.45	1
1	Actuator Control Panel	0.45	1
1	Power Status Panel	1.8	4
1	Model Controller	0.45	1
Add'l	Knobs And Dials	1.4	3
2	Master Controllers	9.0	20
Add'l	Sheet Metal And Wiring	11.3	25
1	Adjustable Seat	1.4	3
	Interface	1.4	3
	Total	42	93

CONTROL CONSOLE WEIGHT ESTIMATES

TABLE 2-3

WEIGHT SUMMARY
FOR
AUXILIARY VIEWING BOOM

TV	16 Kg	(35 lb)
Lights	2.2 Kg	(5 lb)
Extendible Boom		
Be Members	.082 Kg/m	(.055 lb/ft)
Hinges + Wires	.216 Kg/m	(.145 lb/ft)
Total for 18.3m(60 ft)	5.5 Kg	(12 lb)
Extension Mechanism	9.1 Kg	(20 lb)
Roll & Pivot Joint At Root Point		
Motor/ea.	.23 Kg	(. 5 lb)
Harmonic Driver/ea.	.52 Kg	(1.1 lb)
Support Structure/ea	.9 Kg	(2 lb)
Total for Both	3.3 Kg	(7.2 lb)
Roll, Pivot, Tilt Joint at TV End		
Motor/ea	.19 Kg	(.4 lb)
Harmonic Driver/ea	.27 Kg	(.6 lb)
Support Structure/ea	.68 Kg	(1.5 lb)
Total for All Three	3.4 Kg	(7.5 lb)
Root Points (3)	6.8 Kg	(15 lb)
End Connector	6.8 Kg	(15 lb)
Total	55 Kg	(116.7 lb)

summarized in Table 2-4 . The material comparisons for the same φ, γ, and ℓ are the most significant. Beryllium offers significant potential weight savings (a factor of 2 or more) however 6061-T6 aluminum (the next best choice) was selected for the reference design until certain unknowns relative to beryllium (or beryllium alloys) are resolved.

Table 2-5 summarizes weight trade offs against tip force for an aluminum boom. The weight available for the boom tubes is the difference between the maximum allowable weight [454 Kg (1000 lb)] and the sum of all weights (including actuators, etc.) excluding the boom tube weight. Since the available weight decreases as tip force is increased, it is clear that an optimum choice of force versus weight exists. The curves shown in Figures 2-1 and 2-2 illustrate the parameters involved in final selection of the boom geometry. These curves are based on a tip force of 111N (25 lbs) which was judged as a reasonable compromise between boom weight tip force and tip deflection. As shown in Figures 2-1 and 2-2 , the assumed deflection limit (taken about equal to the shuttle berthing center line misalignment - see Appendix 1.0) in conjunction with the specified diameter limit establishes a boom tube thickness of 4.8mm (0.19 in) and a boom tube weight (total including transitions , etc.) of 142 Kg (315 lbs). If, however, the diameter were allowed to increase, a more optimum boom configuration could be achieved. If, for example, the thickness is determined by the minimum practical working thickness [say 1.8 mm(.07 in)], then a near optimum boom configuration is obtained with a 38 cm (15 in) diameter. The weight and deflection [at 111 N (25 lbs) tip force] for this boom would be 88 Kg (195 lbs) and 8.4 cm (3.3 in). (See Volume III "Boom Loads and Structural Analysis" for further details).

By considering the additional possible weight reduction offered by use of beryllium, it is clear that the shuttle imposed 22.9 cm (9 in) diameter should be seriously re-examined and that studies to resolve the unknowns relative to the use of beryllium should be initiated. On this basis, a total boom weight of $\approx$ 100 Kg (220 lbs) appears feasible.

Cantilevered Thin Wall Circular Tube Of Dimensions r, t, ℓ

Material	E (lb/in^2)	ρ (lb/in^3)	σ_{Tu} (lb/in^2)	σ_{Ty} (lb/in^2)	Same (t, r, ℓ, σ_B) (ζ/ζ_{Al})	$\left(\frac{wt}{wt_{Al}}\right)$	Same (ζ, r, ℓ) $\left(\frac{t}{t_{Al}}\right)$	$\left(\frac{\sigma}{\sigma_{Al}}\right)$	$\left(\frac{wt}{wt_{Al}}\right)$	$\frac{F_{tip}}{F_{tip}Al}$
Al (6061-T6)	10×10^6	0.098	45×10^3	40×10^3	1.000	1.000	1.000	1.00	1.00	1.00
Be (.0175 BeO)	44×10^6	0.066	*70×10^3	*50×10^3	0.227	0.675	0.227	4.40	0.153	1.00
Mg (AZ31B-F)	6.5×10^6	0.064	37×10^3	26×10^3	1.540	0.653	1.540	0.65	1.01	1.00
Ti(Ti-6Al-4V)	16×10^7	0.160	140×10^3	128×10^3	0.625	1.64	0.625	1.600	1.02	1.00

*Cross rolled Be sheet

For Bending

stress = $\sigma_B = \frac{Mr}{I} = \frac{M}{\pi r^2 t}$

deflection = $\zeta = \frac{M\ell^2}{3EI} = \left(\frac{M\ell^2}{3\pi}\right)\left(\frac{1}{Er^3 t}\right)$

weight = wt = $\pi d t \ell \rho$

For Torsion

stress = $\sigma_T = \frac{Tr}{J} = \frac{T}{2\pi r^2 t}$

$J = 2I$

when T = M, $\sigma_T = \frac{\sigma_B}{2}$

TABLE 2-4
BOOM MATERIAL COMPARISONS

PART DESCRIPTION	FORCE LEVEL					
	44.5 newtons	(10 lb)	111 newtons	(25 lb)	222 newtons	(50 lb)
Dedicated TV Boom Assembly (1)	53 kg	(117 lb)	53 kg	(117 lb)	53 kg	(117 lb)
Actuators (7)	43 kg	(95 lb)	105 kg	(231 lb)	165 kg	(364 lb)
End Connectors (2)	7.3 kg	(16 lb)	18 kg	(39 lb)	35 kg	(78 lb)
Power System (1)	1.8 kg	(4 lb)	2.3 kg	(5 lb)	2.7 kg	(6 lb)
Control System (1)	2.7 kg	(6 lb)	2.7 kg	(6 lb)	2.7 kg	(6 lb)
TV System (2)	37 kg	(82 lb)	37 kg	(82 lb)	37 kg	(82 lb)
Control Console (1)	45 kg	(100 lb)	45 kg	(100 lb)	45 kg	(100 lb)
Clutches (7)	6.4 kg	(14 lb)	16 kg	(35 lb)	32 kg	(70 lb)
Total Wt Except Boom Tubes	197 kg	(434 lb)	279 kg	(615 lb)	374 kg	(823 lb)
Total Weight Allowed	454 kg	(1000 lb)	454 kg	(1000 lb)	454 kg	(1000 lb)
Weight Available For Tubes	257 kg	(566 lb)	175 kg	(385 lb)	80 kg	(177 lb)

Note

Σ (Dedicated Boom + Power System + Control System + TV System + Control Console) = 310 lbs

$\Sigma Wt_{(Boom)\ Avail} = 690$ lbs

TABLE 2-5
SUMMARY OF MANIPULATOR SYSTEM WEIGHT VS TIP FORCE

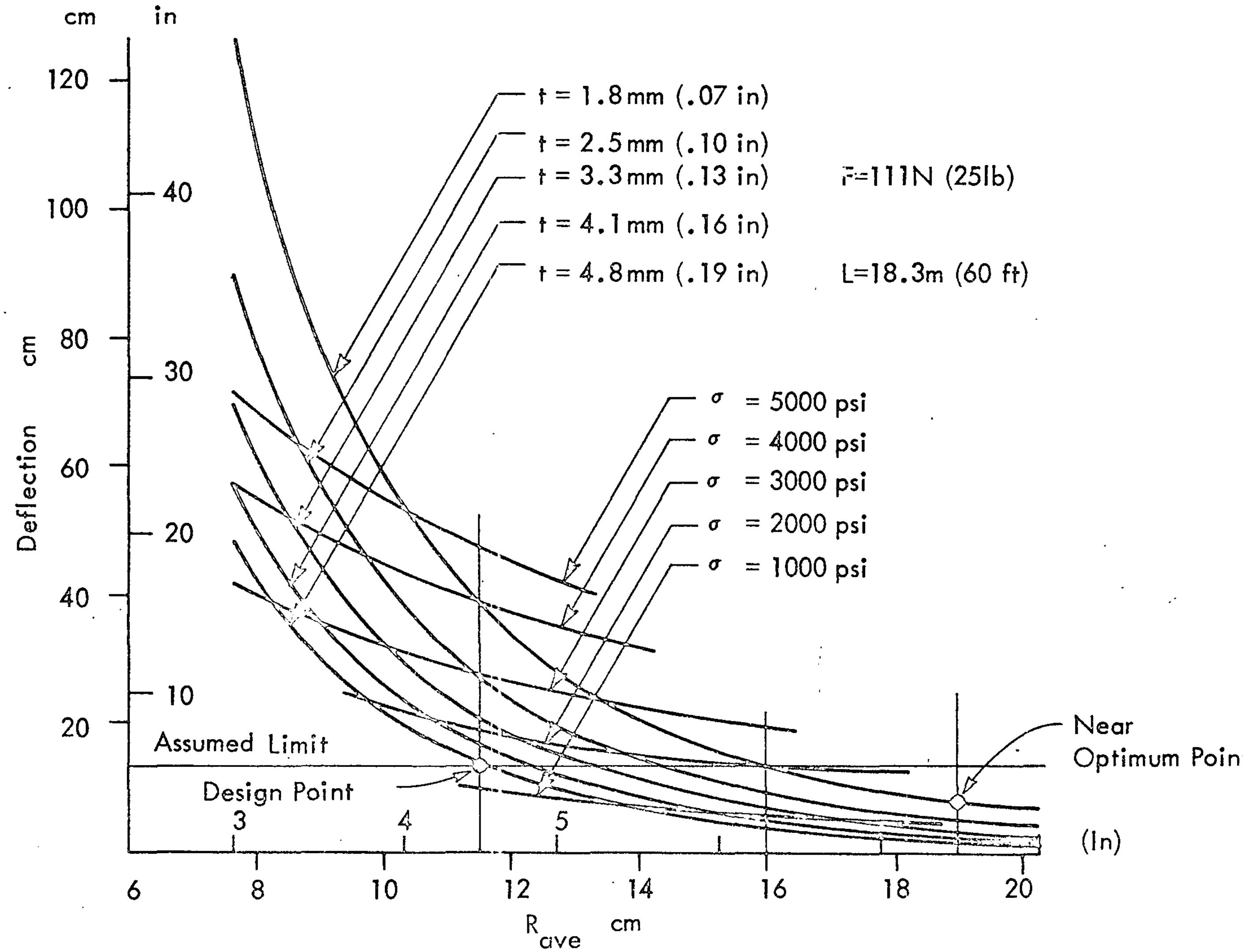


FIGURE 2-1.
DEFLECTION TRADE OFF CURVES FOR ALUMINUM BOOM

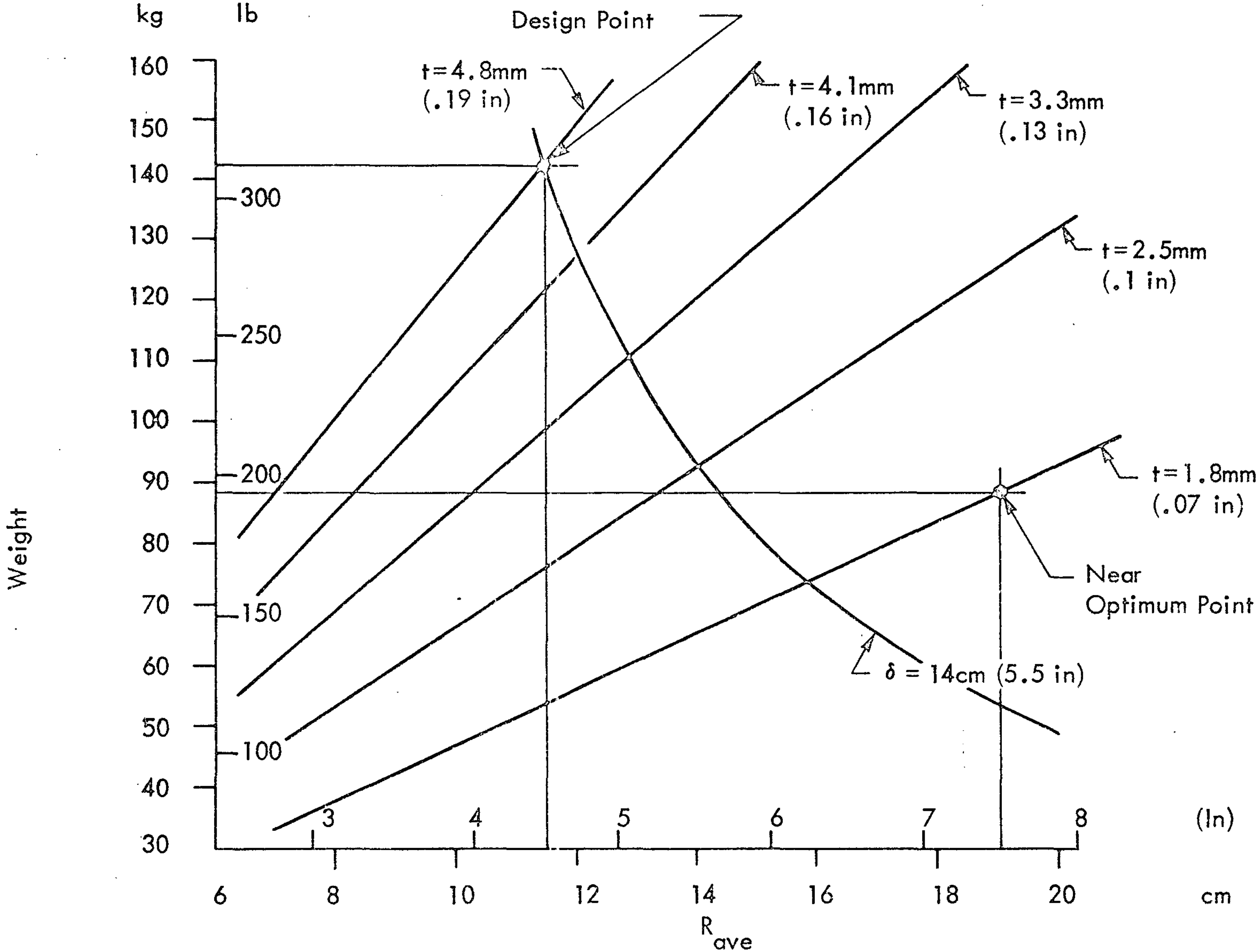


FIGURE 2-2
WEIGHT TRADE OFF CURVES FOR ALUMINUM BOOM

APPENDIX 3.0

3.0 SYSTEM REQUIREMENTS ANALYSIS

A brief summary of how the selected manipulator system meets the study requirements and ground rules is given below. (The system requirements are summarized in Volume III, Section 6.2 "Requirements").

3.1 General Requirements

(1) Task Accomplishment. All of the required tasks can be accomplished. Many of these tasks can be accomplished with only the basic manipulator system (one boom and no end effectors). Special or general purpose end effectors and other auxiliary devices are required to accomplish the full spectrum of tasks.

(2) Interchangeability. The boom, visual system, control console and root points are completely interchangeable between the shuttle and space station. Details of wiring, power source and computers will vary depending on the configurations and availability of these systems on the shuttle and station.

(3) Weight Limit. The manipulator system is within the specified weight limit.

(4) Stowage and Transportability. The manipulator system will fit into shuttle cargo bay for stowage and transport. The boom meets the specified 22.9 cm (9") diameter limitation.

3.2 Subsystem Requirements

3.2.1 Boom

(1) Tip Force and Deflection. Reasonable values of maximum tip force and tip deflection can be provided.

(2) Dexterity. The entire required working envelope can be accessed and the terminator output arranged in any orientation for any location. The 7 DOF boom configuration in conjunction with the walking boom mobility provides the capability to circumvent obstacles as required.

(3) Mobility. The walking boom concept offers complete mobility to any desired working area simply by providing the necessary root points.

(4) Telecommunications. The boom can transmit all of the required command, monitor and video signals to and from end effectors and manipulated objects as required simply by connecting them electrically into the boom end connector.

(5) Interchangeability. The boom is completely interchangeable between the shuttle and space station.

3.2.2 Control Station

(1) Commonality. The identical control station can be used on the shuttle and space station.

(2) 040A Constraints. The control station is compatible with the 040A envelope.

3.2.3 Man-Machine Interface

(1) Crew. Only one operator is required.

(2) Compatibility. The system allows the operator to use his complete dexterous, sensory and adaptive capabilities to a very high degree.

(3) Alternate Modes. The system provides necessary redundancy and back-up modes and allows the operator to override (stop) the boom whenever he deems it necessary.

3.2.4 Visual Systems

(1) Visual Display. High resolution with the depth cues required for close in precise tasks is provided.

(2) Field-of-View. Complete coverage of the overall work area is achieved by use of multiple cameras and a dedicated viewing boom.

(3) Direct Vision. The control console is arranged to take advantage of direct viewing where it is available (the 040A shuttle).

(4) Back-Ups. Redundant cameras and monitors in conjunction with direct viewing stereoscopes provide the necessary back-up capability.

3.2.5 Control System

(1) Boom Behavior. Smooth boom motions can be provided and electronic controlled dynamic damping is provided to eliminate boom oscillations.

(2) Redundancy. Independent dual control components and multiple addresses are used to provide redundancy.

3.2.6 Data Processing and Transmission

(1) Video Quality. Hand wired video transmission precludes ghosting and multipath problems and provides good signal to noise ratio.

(2) Control and Monitor. Parallel pulse code modulation provides good accuracy, and noise rejection capability.

(3) Growth Potential. The selected system provides good growth potential.

3.3 Safety

The manipulator system should increase the overall safety of the shuttle or space station by providing an emergency capability that would otherwise not exist.

3.4 Reliability

The selected manipulator system can meet the anticipated reliability requirements because of the time scale on which the manipulator and related space system will be developed. Initial requirements will be modest because of the ability to implement frequent ground servicing. As requirements become more stringent refined development and experience will have been achieved to keep pace with the increasing requirements.

APPENDIX 4.0

PRELIMINARY DESIGN DRAWINGS

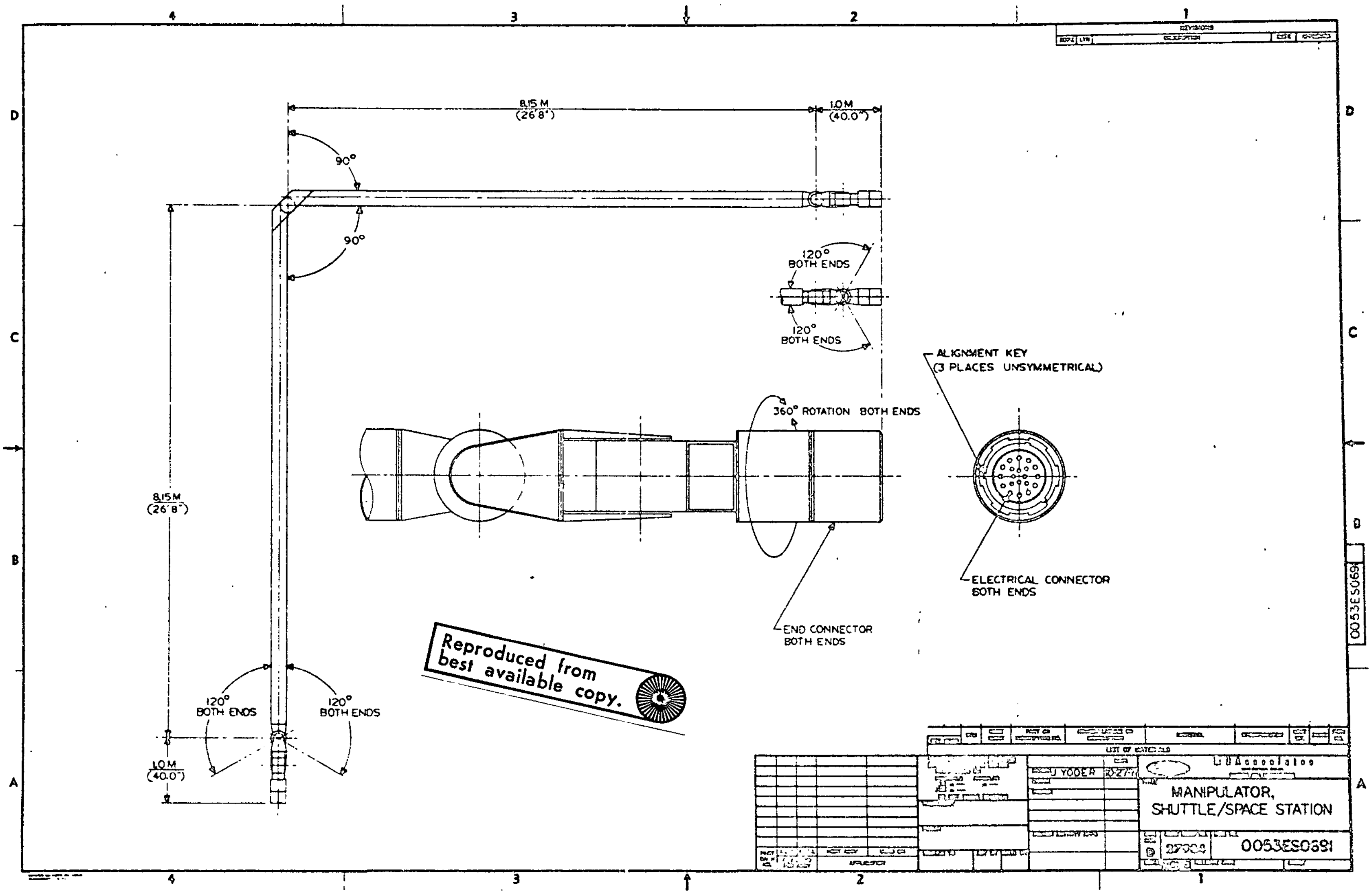


FIGURE 4-1.
MANIPULATOR, SHUTTLE/SPACE STATION

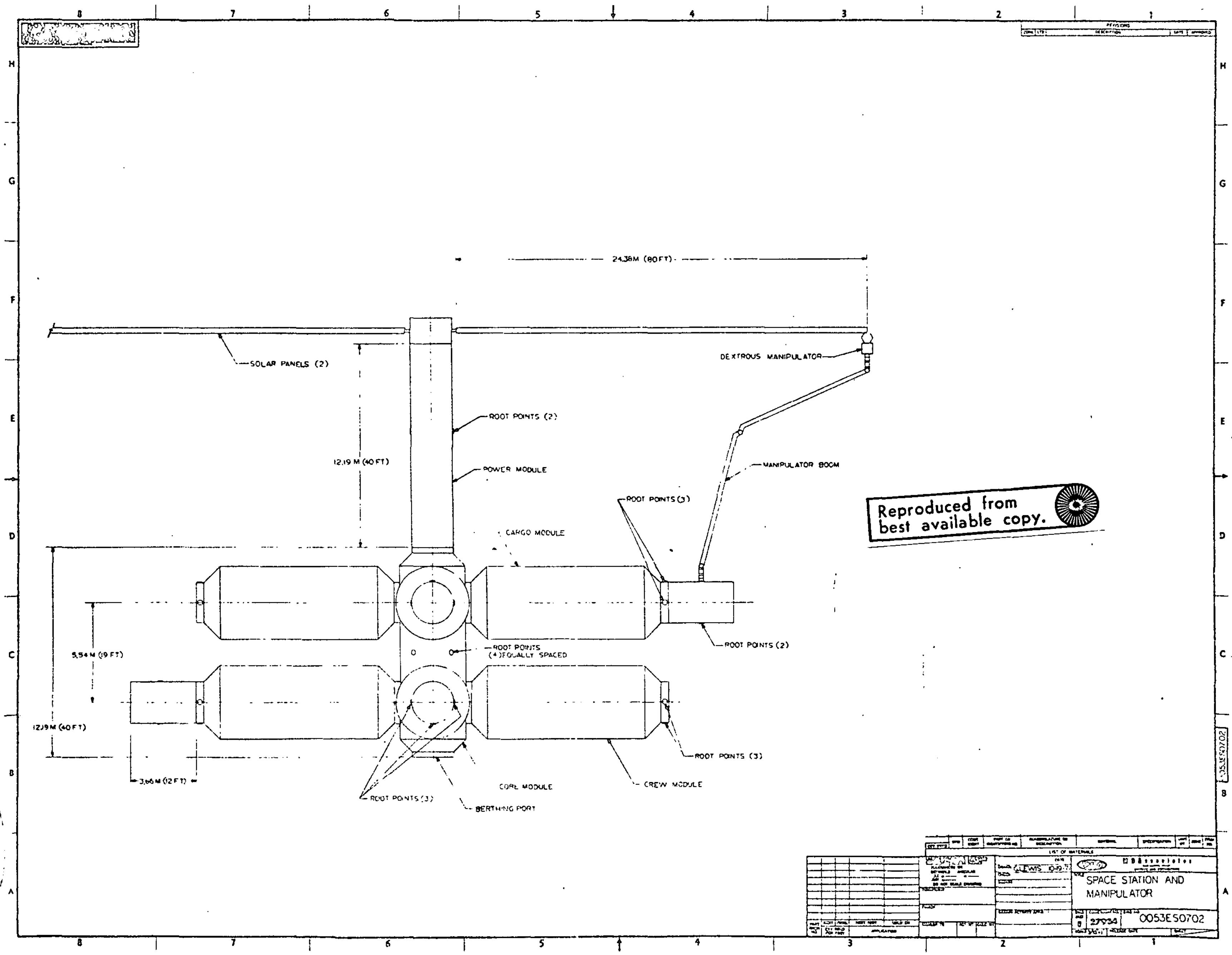


FIGURE 4-2.
SPACE STATION AND MANIPULATOR

3

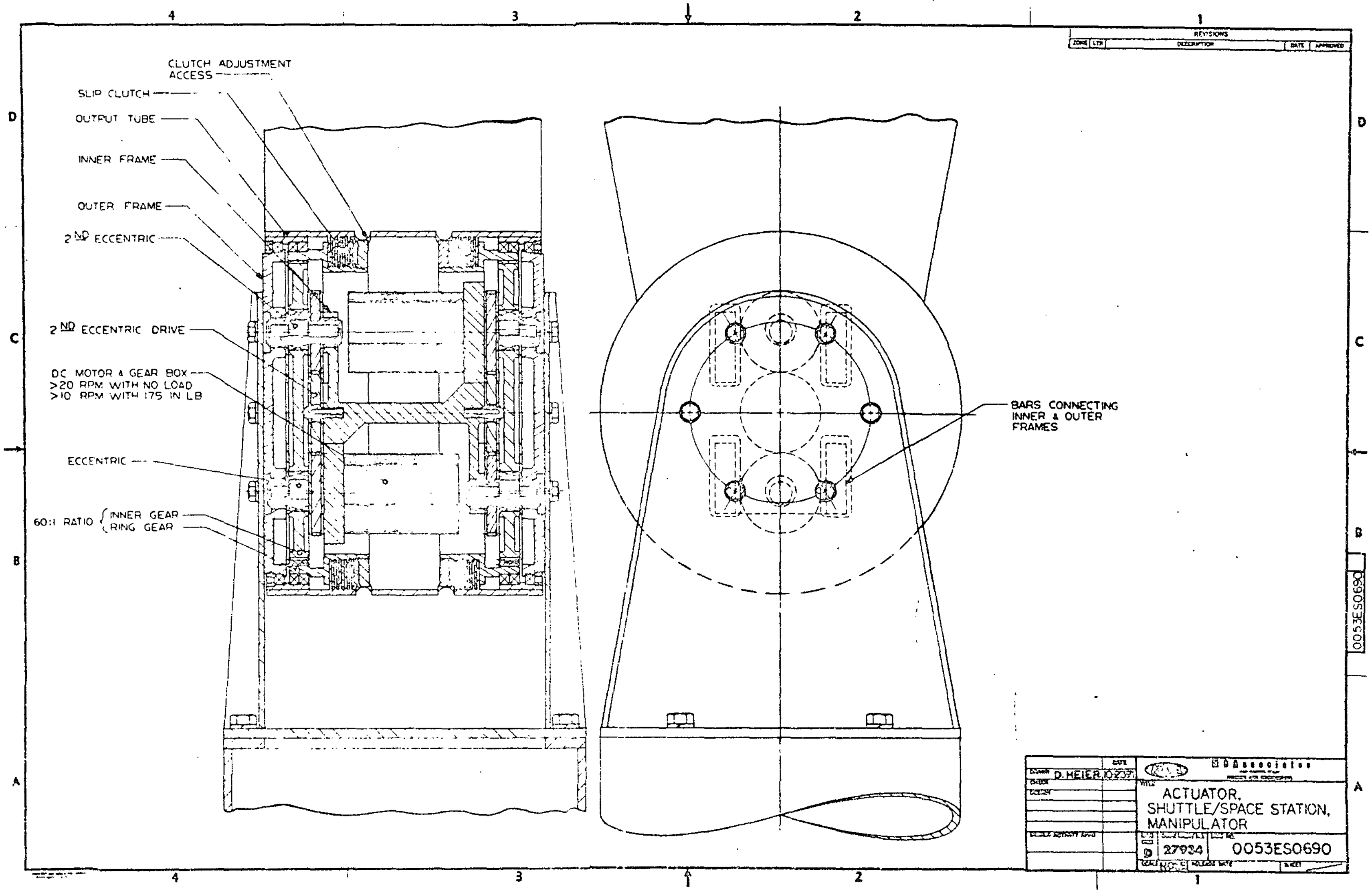


FIGURE 4-3.
ACTUATOR, SHUTTLE/SPACE STATION MANIPULATOR

0282-10123

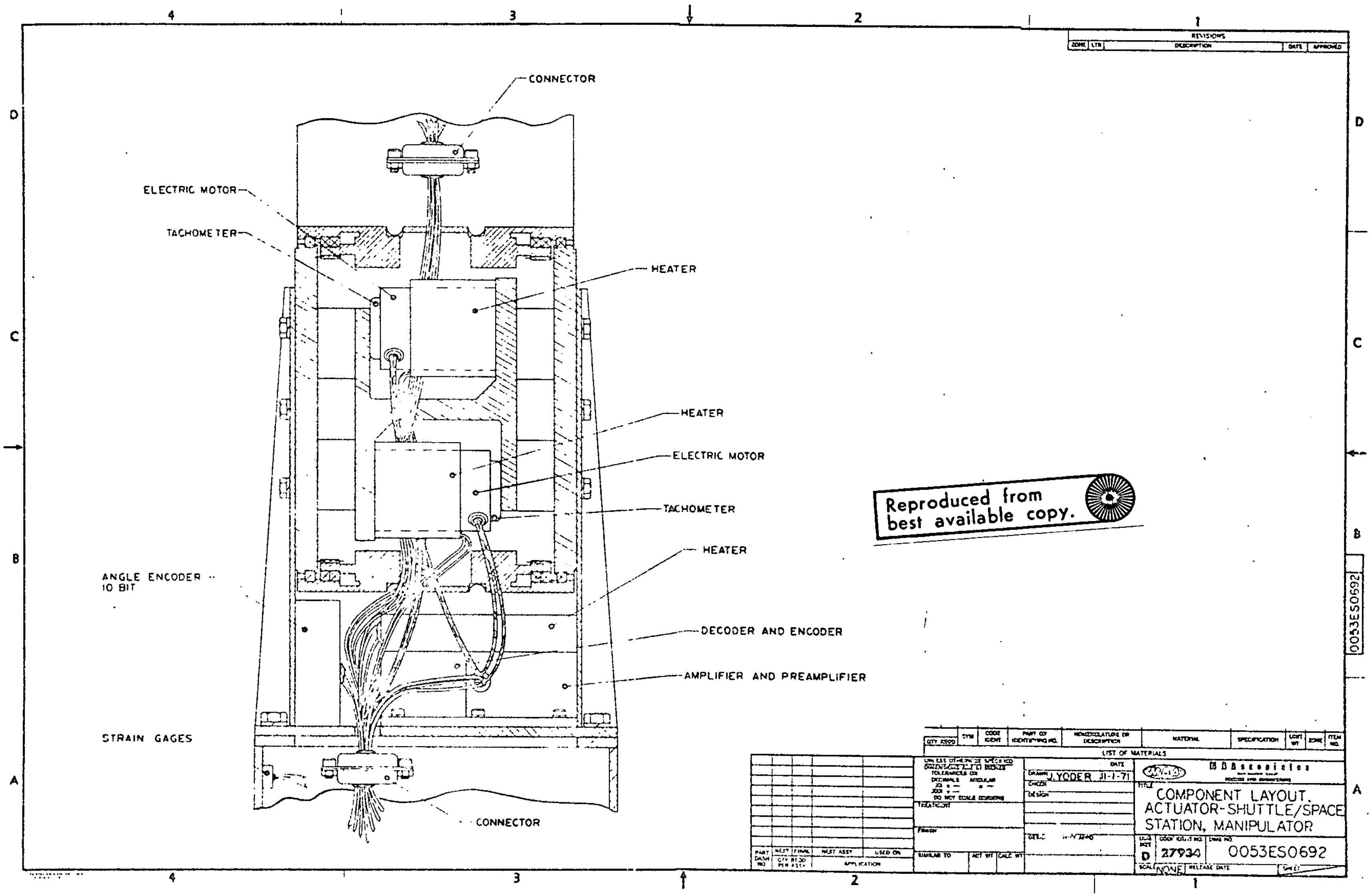


FIGURE 4-4.
COMPONENT LAYOUT, ACTUATOR-SHUTTLE/SPACE STATION, MANIPULATOR

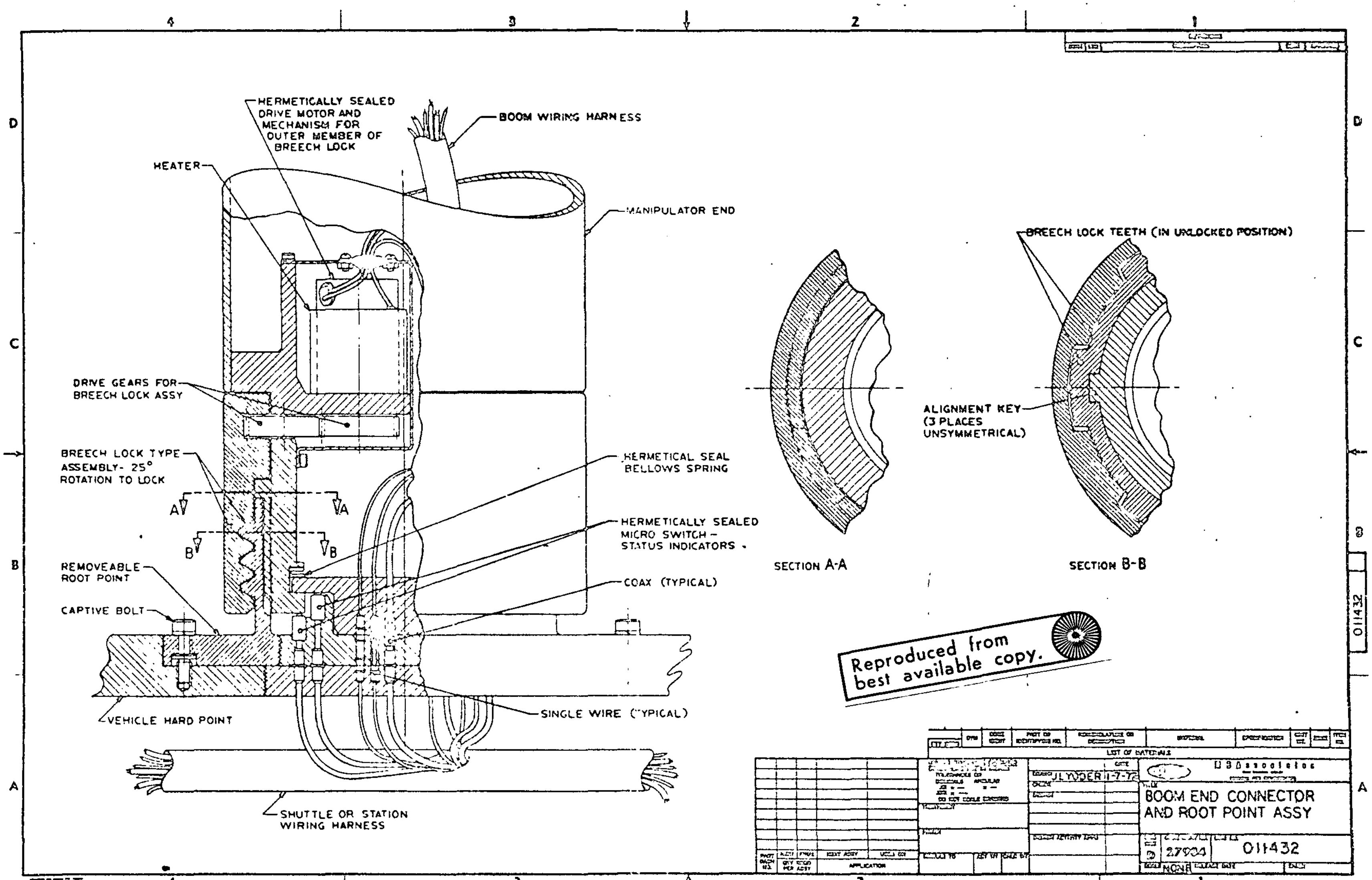


FIGURE 4-5
REFERENCE END CONNECTOR/ROOT POINT CONFIGURATION

3582-10025

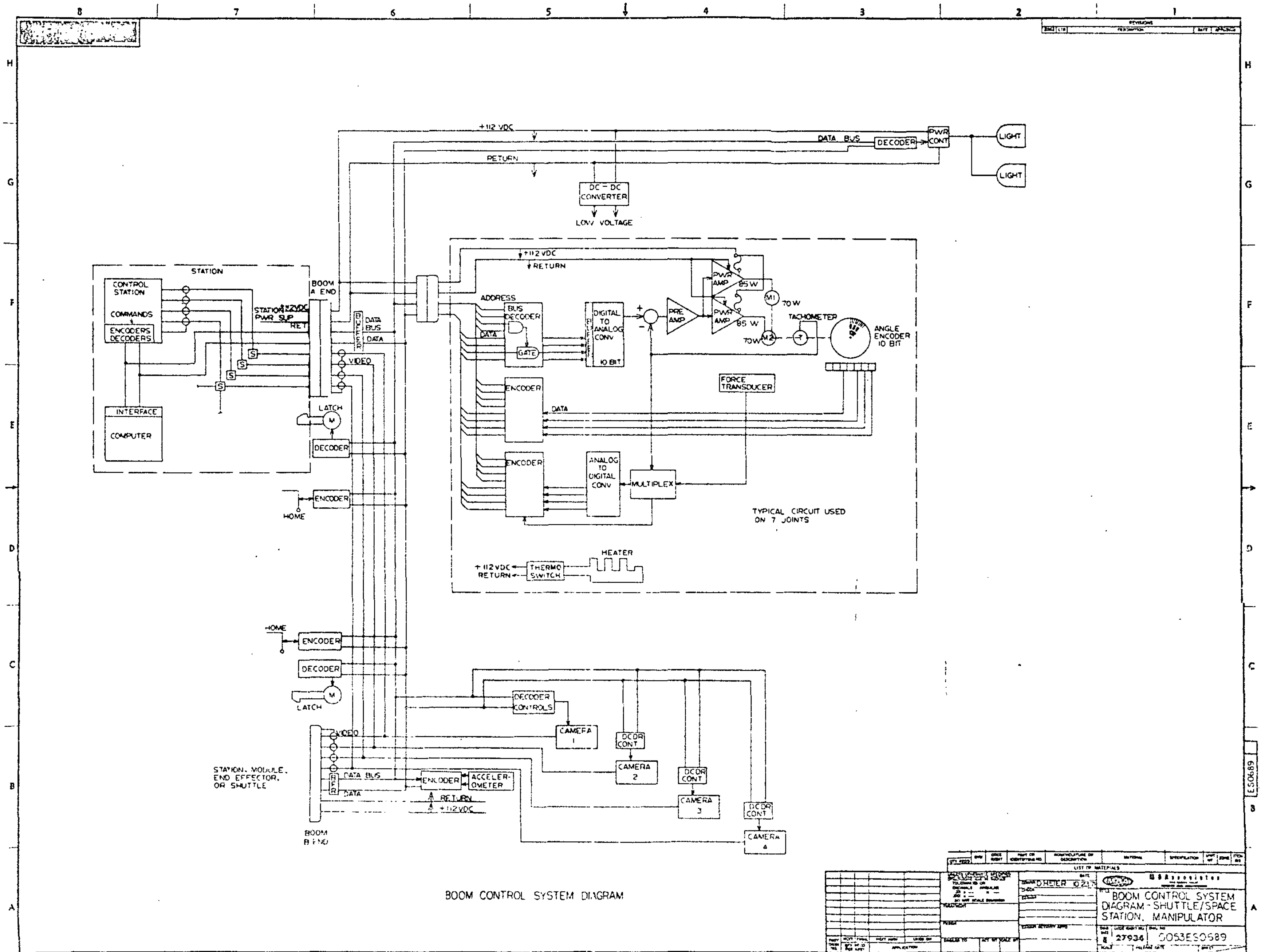


FIGURE 4-6
ELECTRONIC CONTROL SYSTEM FUNCTIONAL BLOCK DIAGRAM

APPENDIX 5.0

CONCEPT DEVELOPMENT AND SELECTION

5.0 CONCEPT DEVELOPMENT AND SELECTION

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 5-1. 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 4.57m (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.

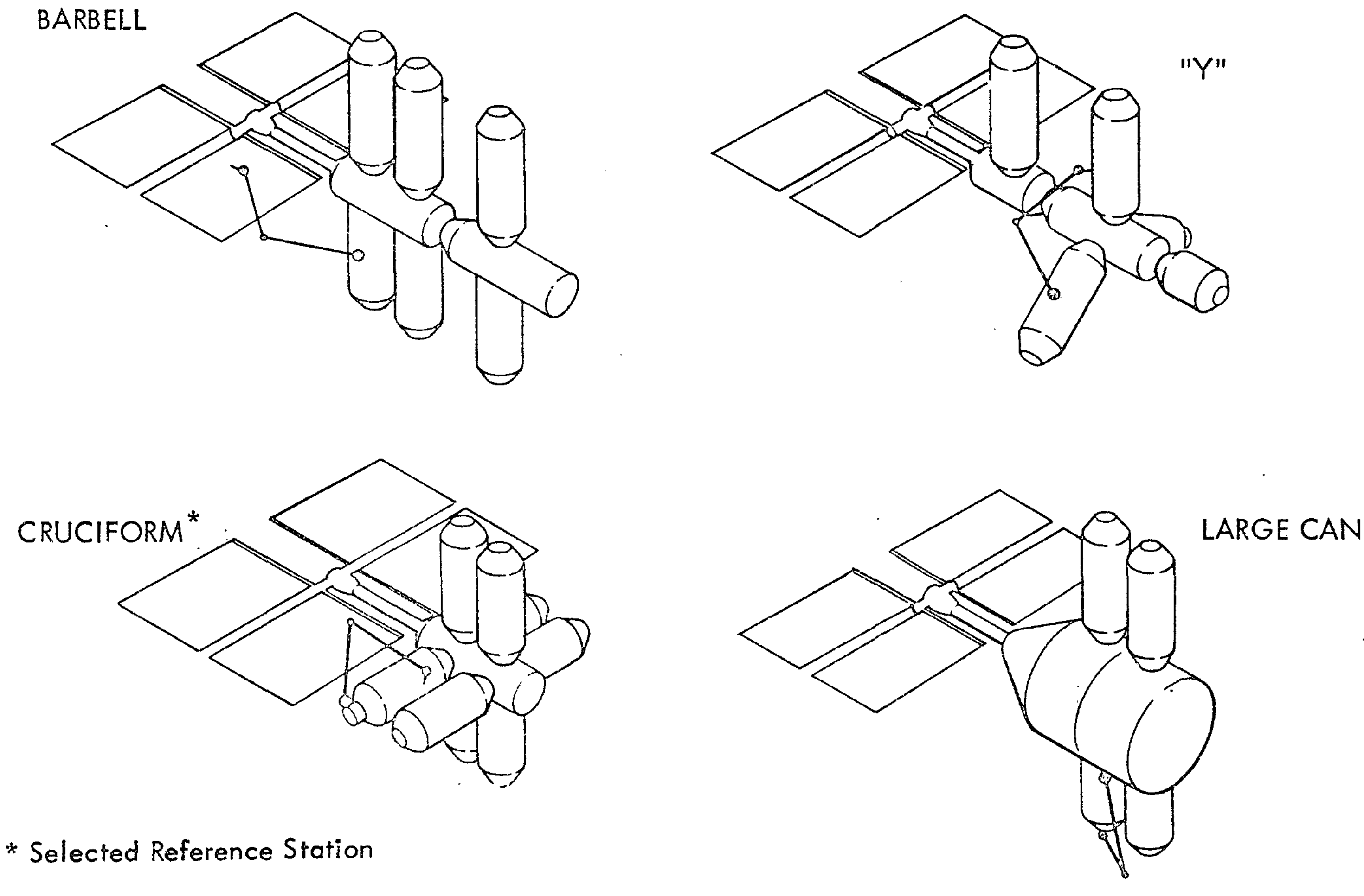


FIGURE 5-1
SPACE STATION CONFIGURATIONS

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:

Common Elements	Different Elements
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 5-2 through 5-6. The boom configuration selection is shown in Figure 5-2. 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.

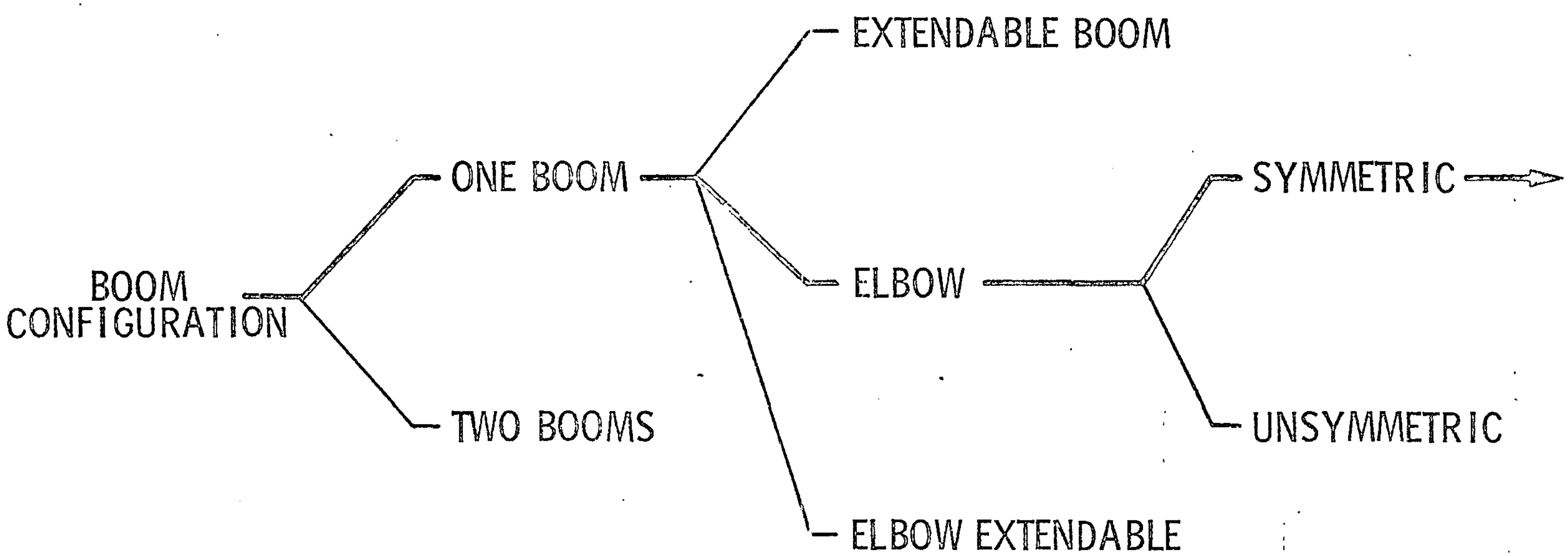
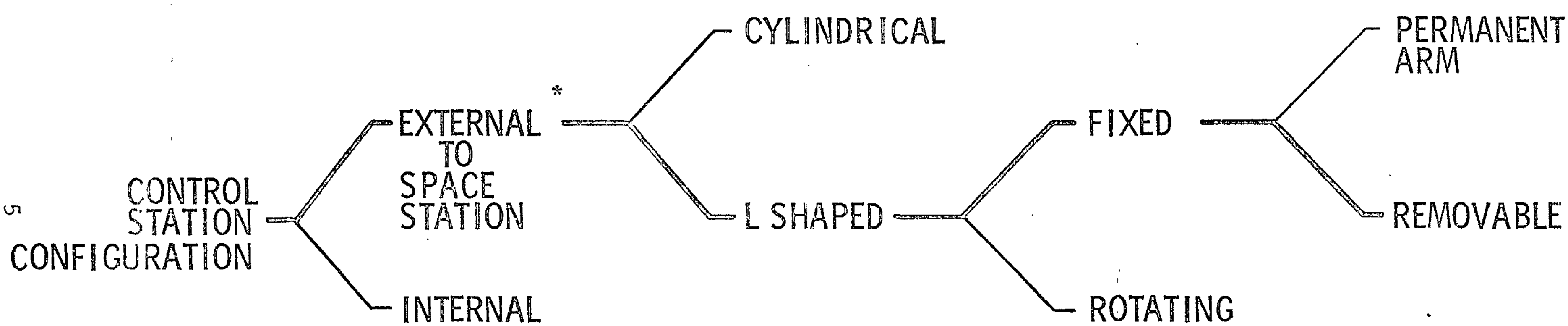


FIGURE 5-2
BOOM CONCEPT SELECTION NETWORK



* Contract Requirement

FIGURE 5-3
CONTROL STATION CONCEPT SELECTION NETWORK

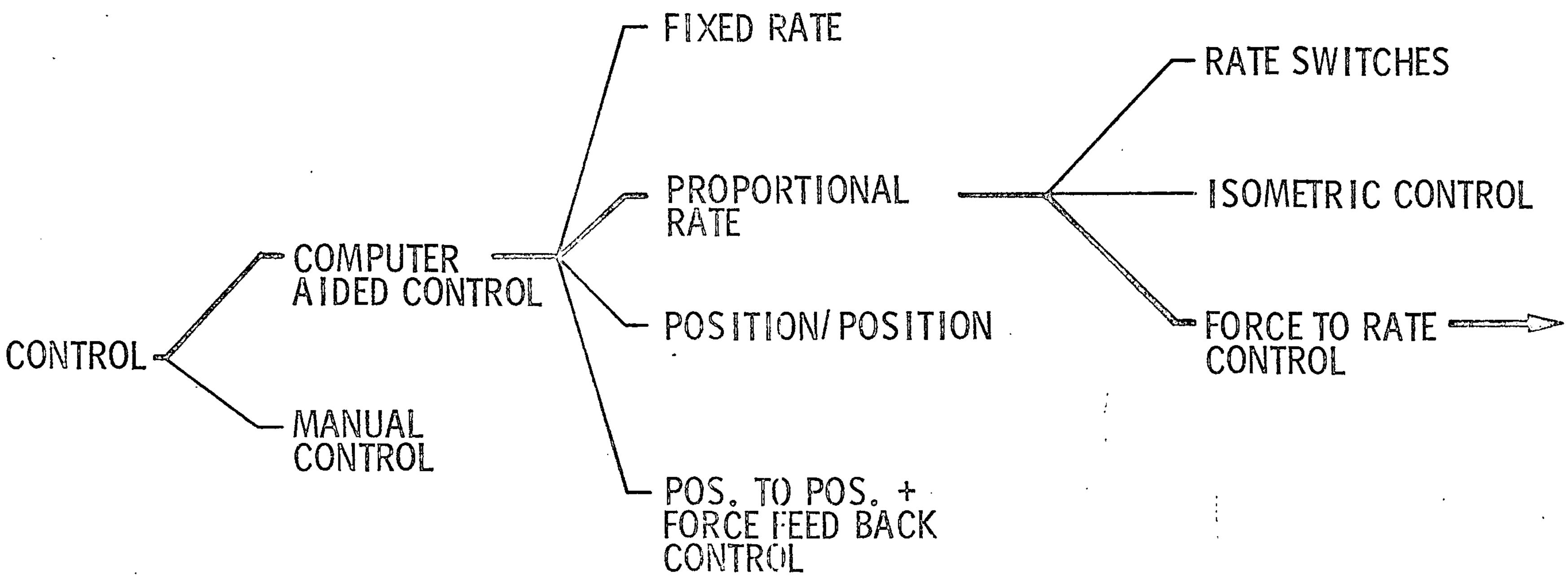


FIGURE 5-4
CONTROL CONCEPT SELECTION NETWORK

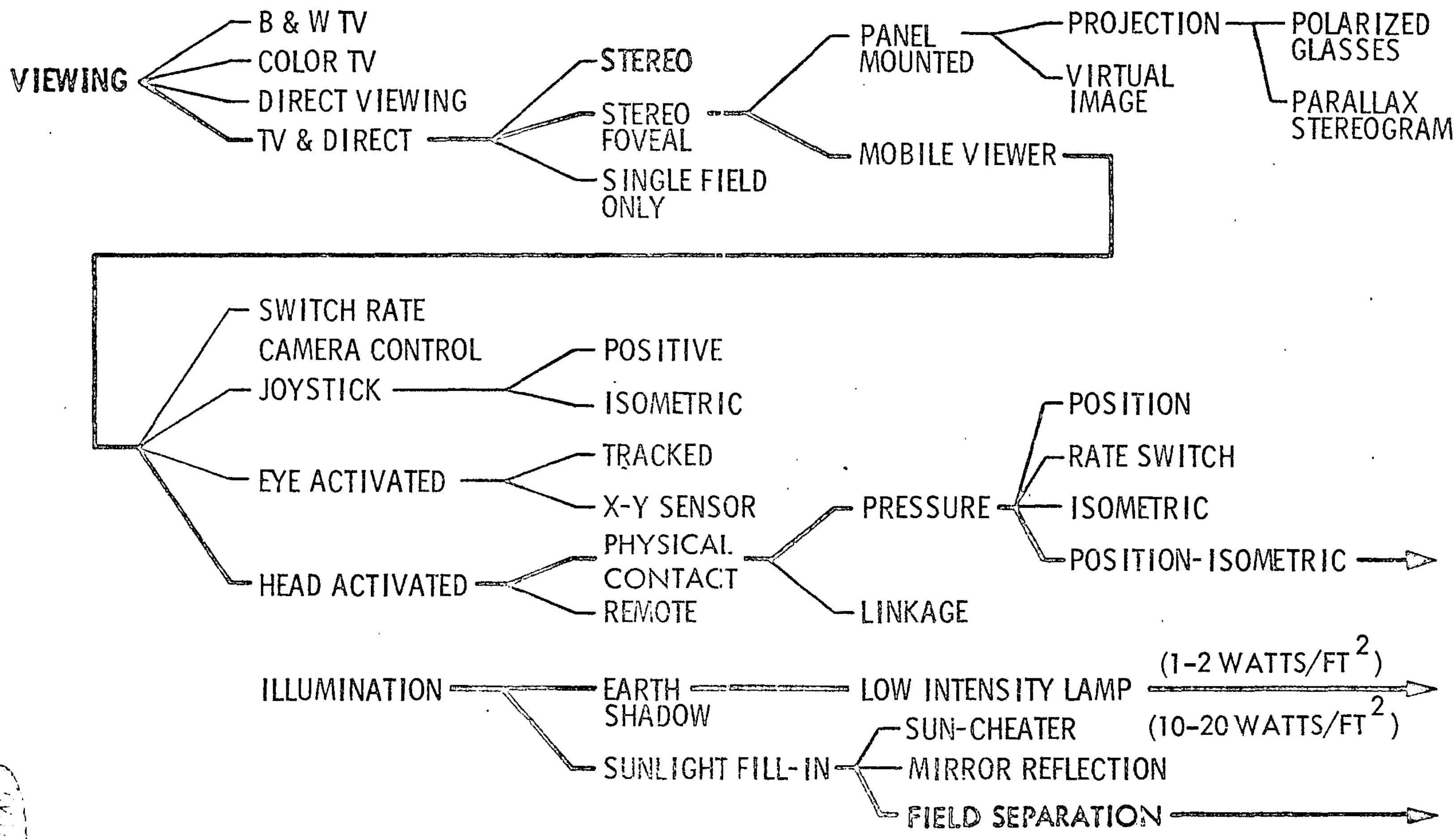


FIGURE 5-5

VIEWING SYSTEM CONCEPT SELECTION NETWORK

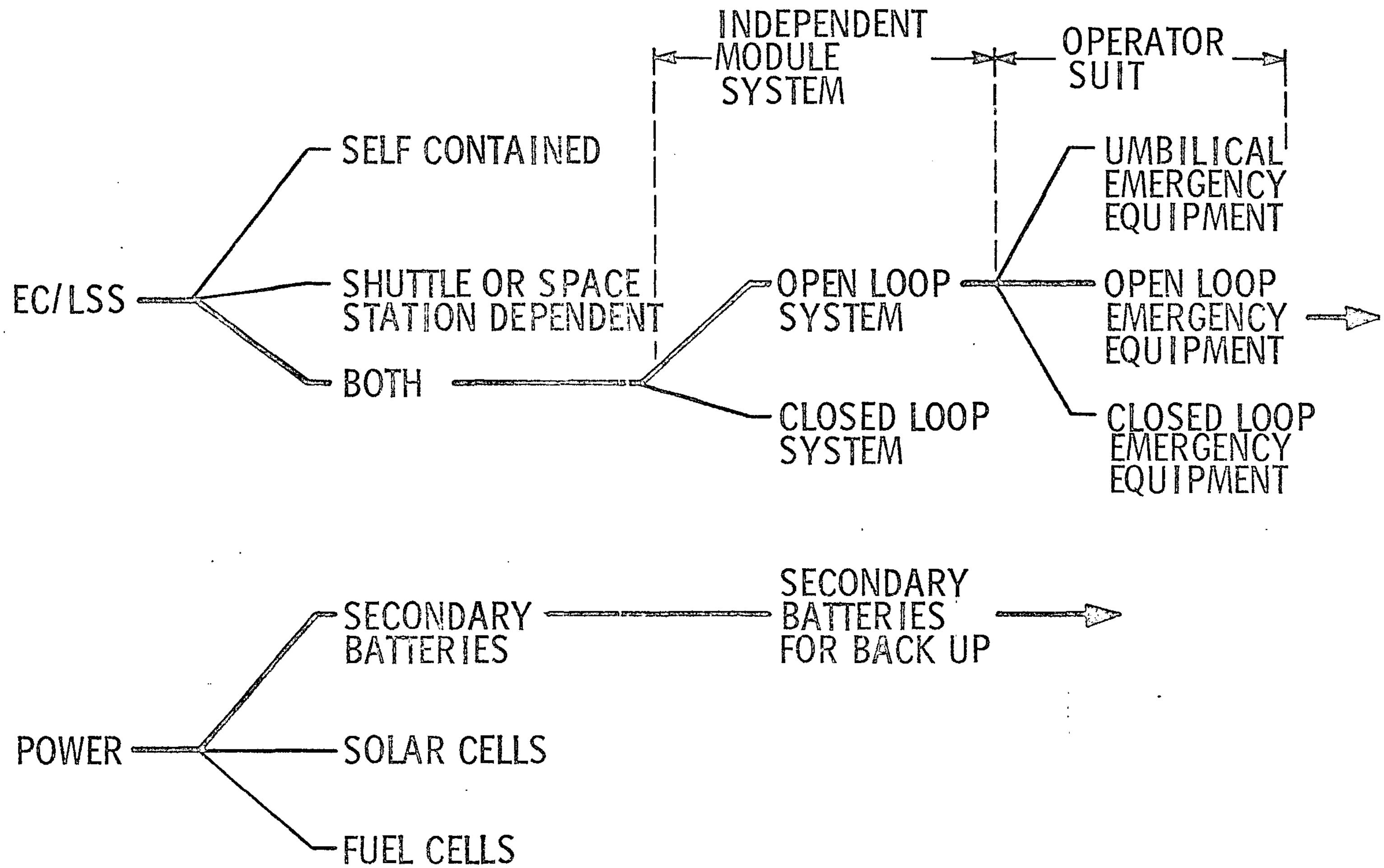


FIGURE 5-6
ENVIRONMENTAL CONTROL LIFE SUPPORT AND POWER SUPPLY SYSTEMS CONCEPT SELECTION NETWORK

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 5.3. 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.

The control concept selection is shown in Figure 5-4. 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 [≤.61 m/sec (2 fps)] and low angular rates (≤3°/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 ~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 inputed 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.

The viewing system concept selection is shown in Figure 5-5. 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/$_{m^2}$ (~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/$_{m^2}$ (~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 5-5, a separate dedicated boom was selected for supporting, locating and controlling additional lights and viewing cameras.

The environmental control, life support and power system selection is shown in Figure 5-6. 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 ($\sim$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 $\leq$ 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 5-7. The manipulator system recommended by MBA is illustrated in Figure 5-8. 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.

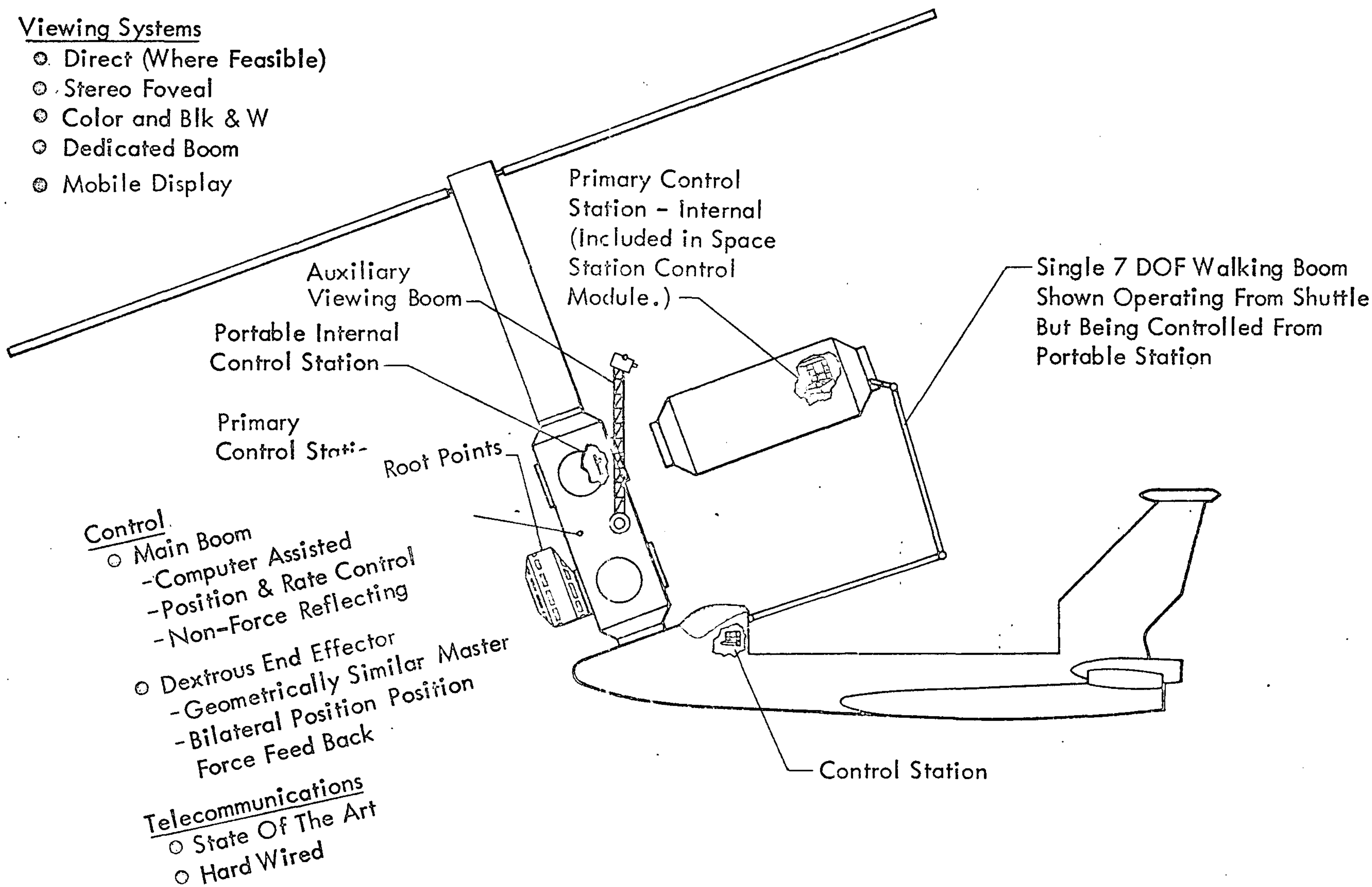


FIGURE 5-7
RECOMMENDED PHASE I MANIPULATOR SYSTEM CONCEPT
WITH CONTROL STATION OPTIONS

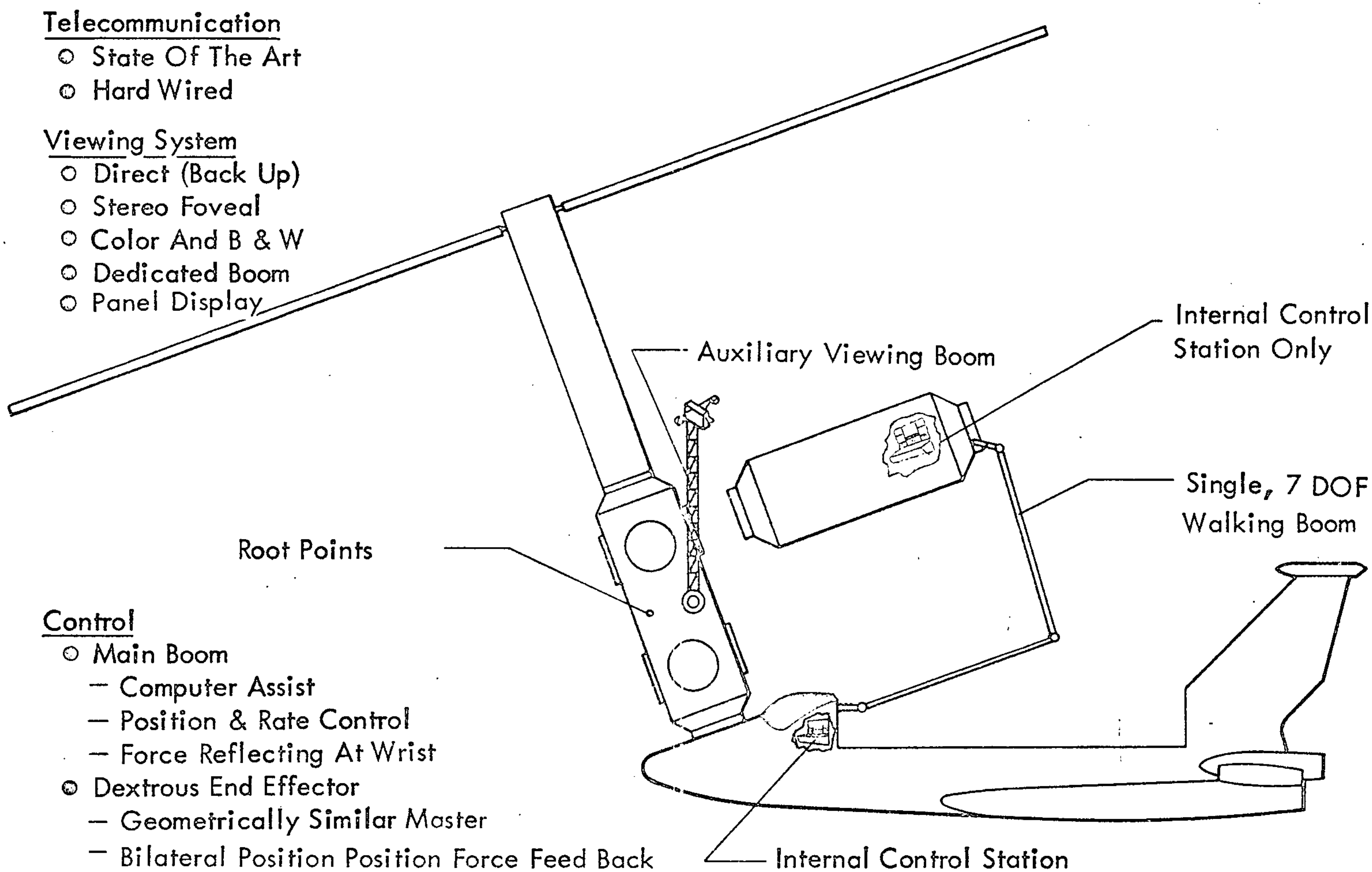


FIGURE 5-8
MSC APPROVED MANIPULATOR SYSTEM CONCEPT

3351-9887

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 5-8.

APPENDIX 6.0

MANIPULATOR KINEMATIC DESIGN RULES

6.0 Boom Mechanical Analysis and Design

6.1 Kinematic Design Rules

The kinematic configuration of the selected manipulator system boom illustrated in Section 2.3 "System Description", Figure 2.3-3 was evolved utilizing a set of design rules developed in this program. These rules along with figures to illustrate their concepts are presented below. The reader is referred to Design Rules, Volume II "Concept Development and Selection", Page 30, for a detailed discussion of them.

MANIPULATOR DESIGN RULES

(1) Design kinematically to accomplish primary tasks it must perform with ease.

(2) To minimize operator training, task time, and task mistakes under stress--kinematic similarity between master controller and slave must be maintained. (Note: By use of a computer it is possible to achieve effective kinematic similarity with physical having, kinematic similarity between master controller and slave arm).

(3) 3 rotational (or orientor) axes should be as close to the terminals as possible. (See figure 6-1).

(4) In the preferred position the three terminator orientor axes should be mutually perpendicular. (See figure 6-2).

(5) In the preferred position, the 3 locator or shoulder axes should be mutually perpendicular. (See figure 6-3).

(6) For spot mounted manipulators the actuator connected to the ground should have a vertical output axis. (See figure 6-4).

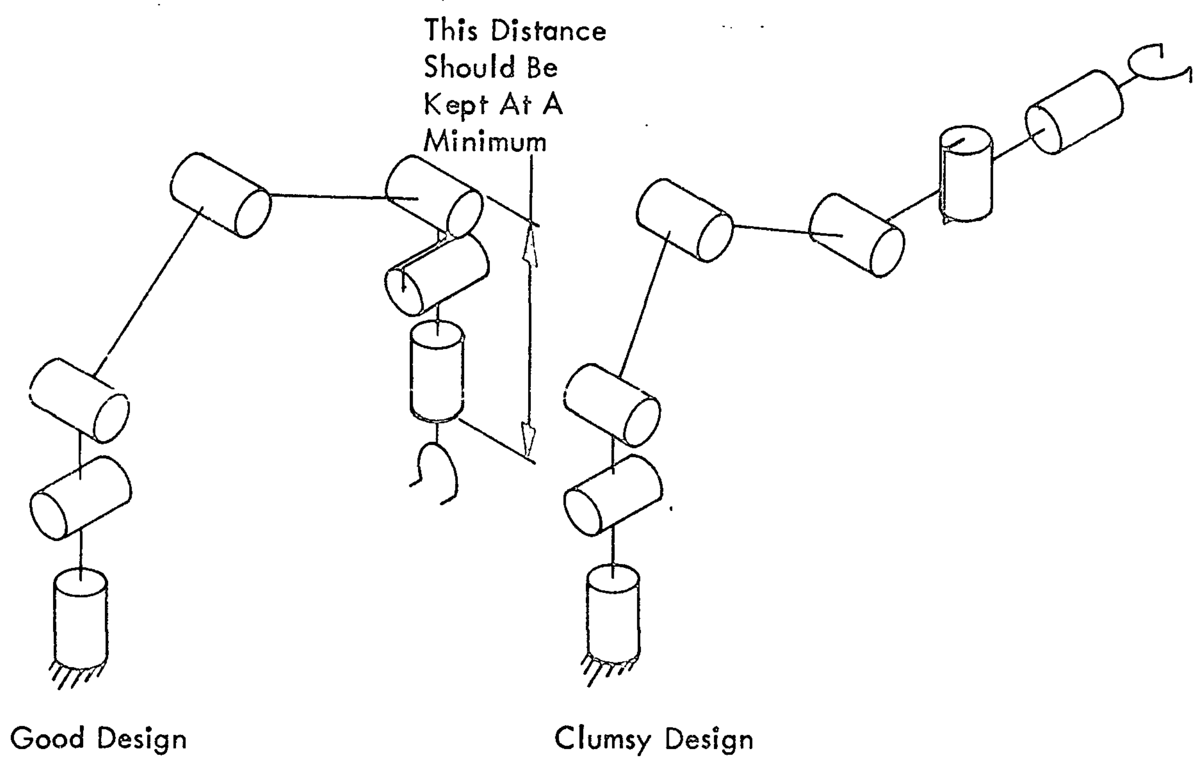


FIGURE 6-1
RULE III ORIENTOR AXES LOCATION

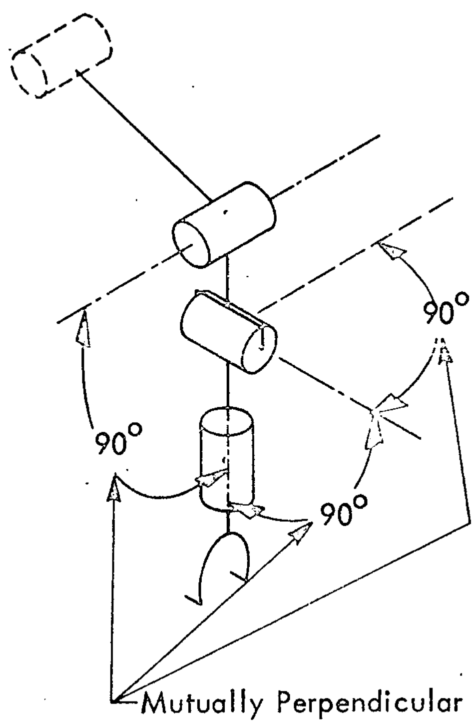


FIGURE 6-2
RULE IV PERPENDICULAR ORIENTOR ACTUATORS
FOR NORMAL OR PREFERRED POSITION

3331-9814

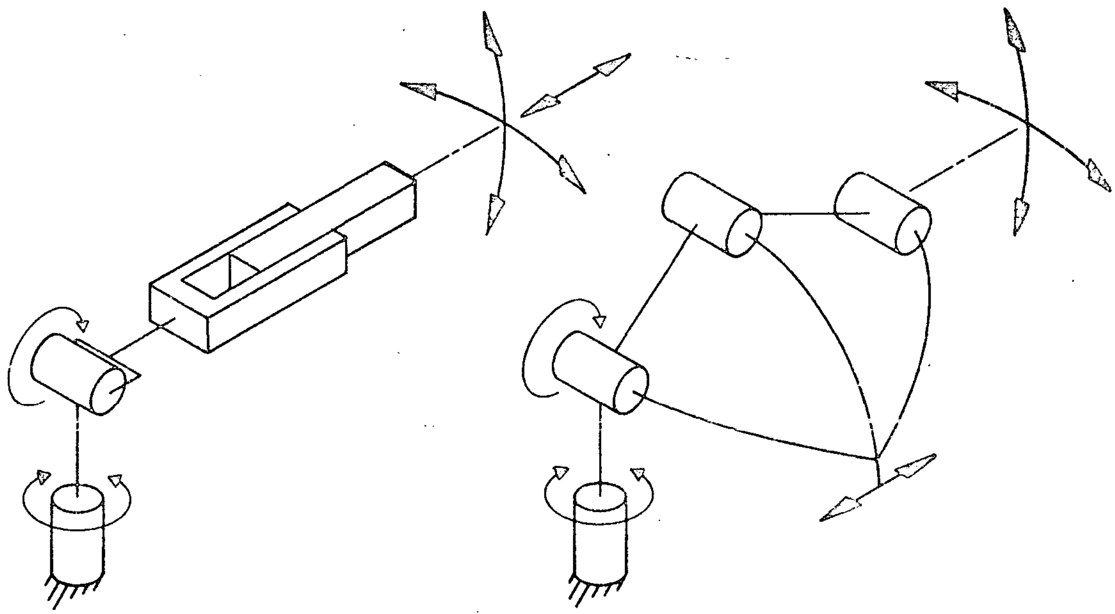


FIGURE 6.3
RULE V MUTUALLY PERPENDICULAR LOCATOR ACTUATORS

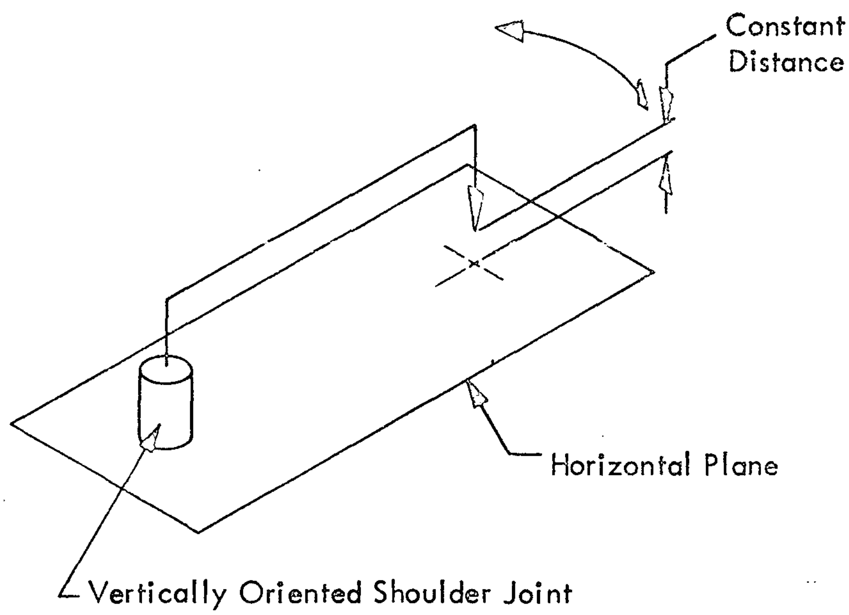


FIGURE 6-4
RULE VI HORIZONTAL TIP MOVEMENT
(SPOT MOUNTED MANIPULATORS)