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

CR 115-482

FINAL REPORT

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

(PRELIMINARY DESIGN)

Volume III - Concept Analysis
Part 1 - Technical

7 January 1972

Prepared For:

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

OFFICE OF PRIME RESPONSIBILITY

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MBAssociates
Bollinger Canyon Road
San Ramon, California 94583

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Approved By:

DONALD F. ADAMSKI
Program Manager

DAVID L. COCHRAN
Senior Vice President
Director of Engineering

MBAssociates
Bollinger Canyon Road
San Ramon, California 94583

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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ABSTRACT

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

The basic manipulator system consists of a single 18.3m (60') long, 7 degree of freedom (DOF), electrically actuated main boom with an auxiliary 3 DOF electrically actuated, extendible 18.3m (60') maximum length, lighting and viewing boom. A 3 DOF 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. A preliminary program estimate has been made for development and flight qualification of the manipulator system, including a dexterous general purpose end effector and including ground simulations, and operator training up to, but not including, orbital flights.

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

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

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

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1.0 DEFINITIONS

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

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

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

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

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

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

CRT - Cathode ray tube

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

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

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

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

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

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

EC/LSS - Environmental Control/Life Support Systems.

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

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

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

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

PCM - Pulse coded modulation - system of data transmission.

PWM - Pulse width modulation - efficient power amplification method.

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

SOW - Contract Statement of Work.

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

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

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

2.0 SUMMARY

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 the concepts evolution and evaluation studies. The results of these studies and a recommended concept were presented by MBA to NASA in a briefing at MSC on August 30, 1971. The briefing aids are summarized in MBA document MB-R-71/85. The analysis of the various concepts and the rationale leading to the concept approved by MSC for further study are given in more detail in Volume II, "Concept Selection" of this final report. The present document presents the analyses and preliminary design of the selected concept.

Space station assembly and shuttle cargo handling tasks have been 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 has also been 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 relock 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 appendices. 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. (See Volume III - Part 2)

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 22.9cm (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

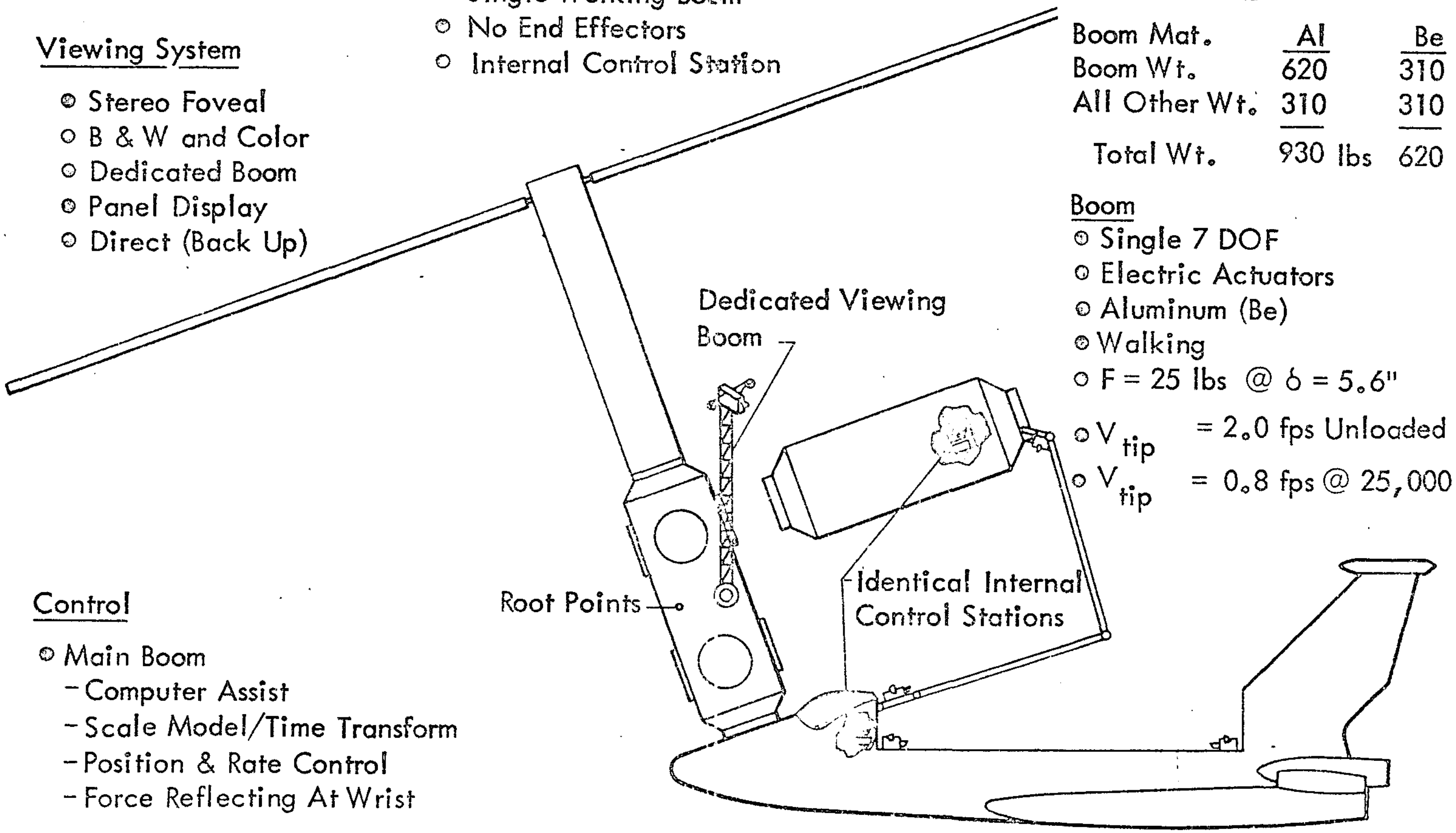
The basic manipulator system is illustrated schematically in Figure 2.3-1 and it is shown in more detail in preliminary design drawings 0053ES0689, 0053ES0690, 0053ES0691, 0053ES0692, 0053ES0702 and 011432. Table 2.3-1 presents a weight breakdown of the major system components and Table 2.3-2 summarizes 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 2.3-1
SCHEMATIC PRELIMINARY DESIGN OF MSC APPROVED MANIPULATOR SYSTEM

TABLE 2.3-1

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 @ $\delta = 5.6''$

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
$\alpha/\epsilon = 1.04$	$\epsilon_{\text{Shield to Boom}} = 0.1$
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 2.3-2.
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 2.3-1, 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 ± 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 2.3-2. 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 0053ES069Z

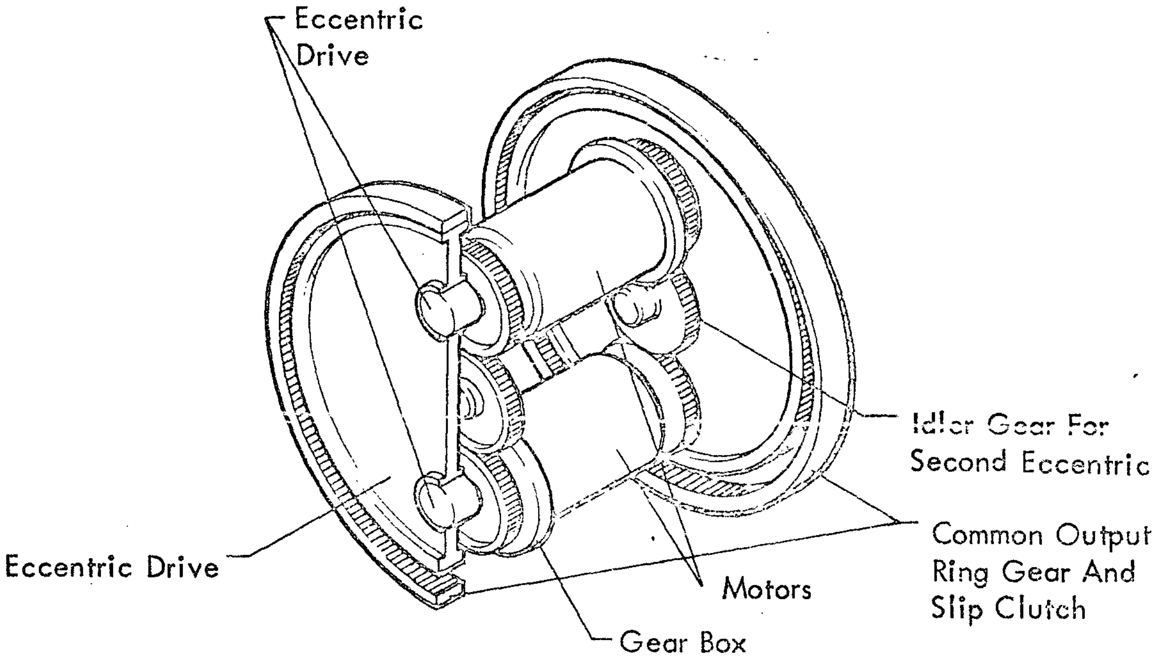


FIGURE 2.3-2
SCHEMATIC OF SELECTED DOUBLE
DIFFERENTIAL GEAR ACTUATOR CONFIGURATION

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 2.3-3. 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 presented in Section 6.3.1 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 2.3-4.

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.

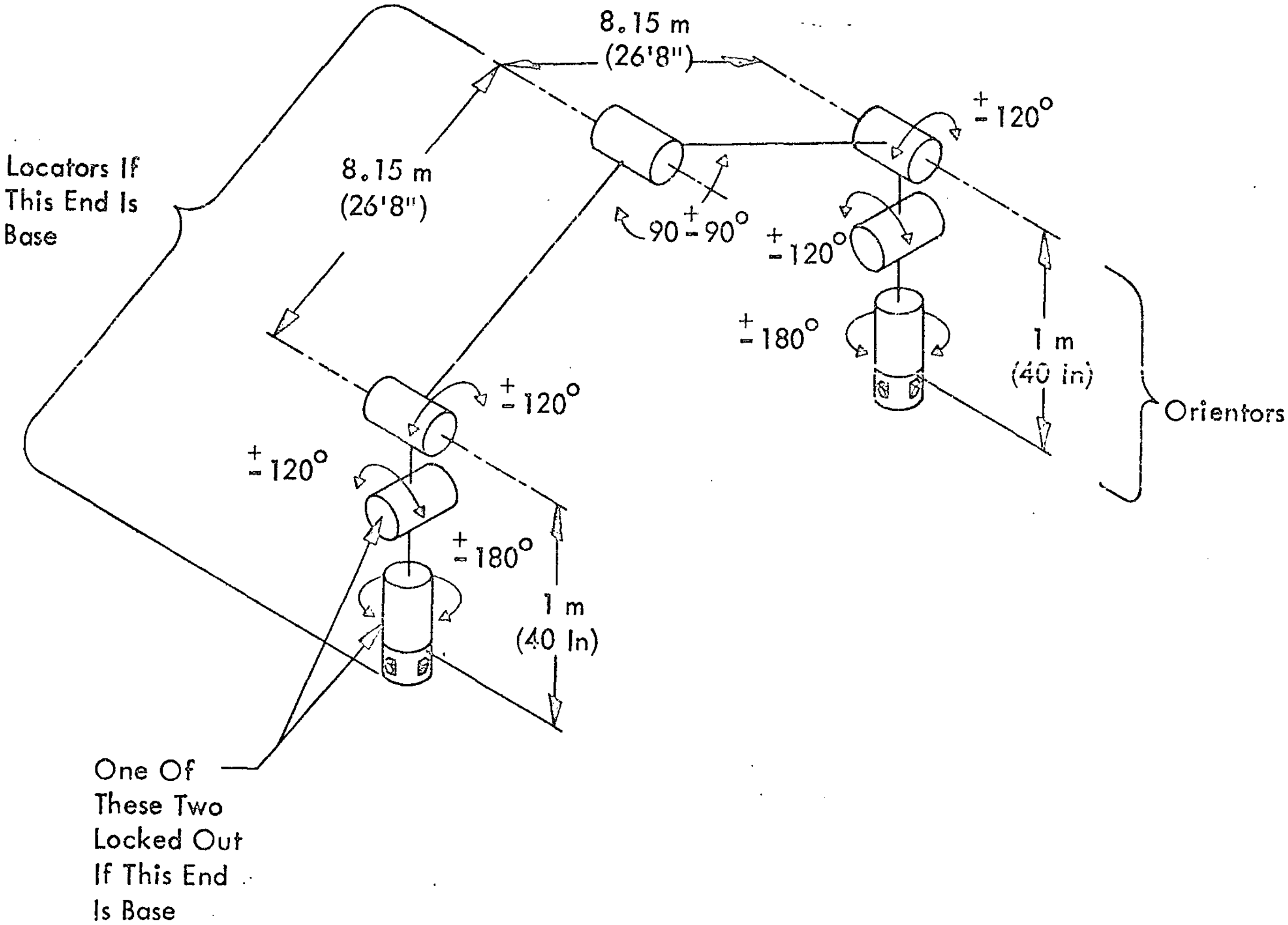
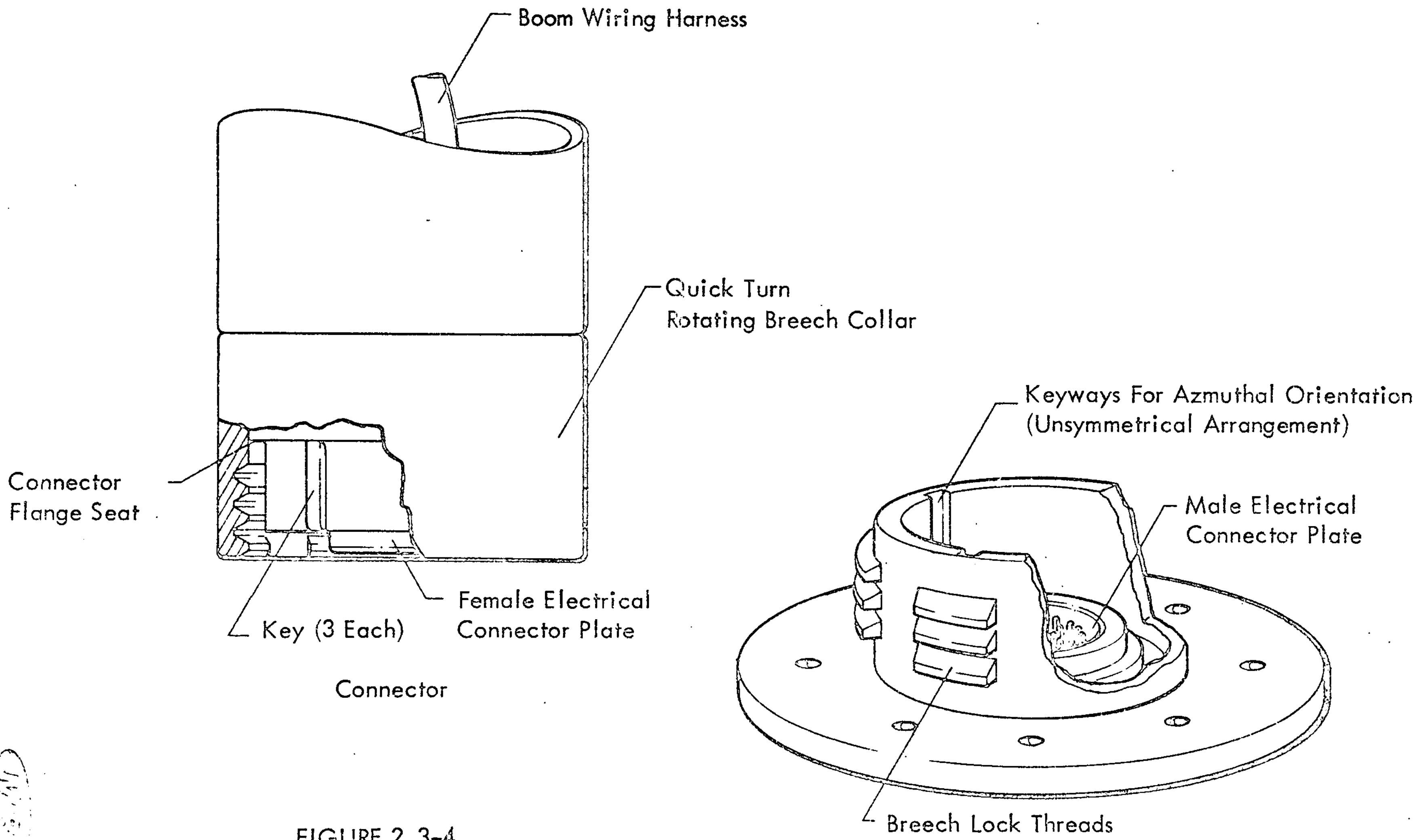


FIGURE 2.3-3
KINEMATIC ARRANGEMENT OF SELECTED SYMMETRIC
BOOM-JOINT CONFIGURATION



Connector

Root Point

FIGURE 2.3-4.
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 2.3-5. The manipulator controllers and the control panel layout are shown in Figures 2.3-6 and 2.3-7 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/

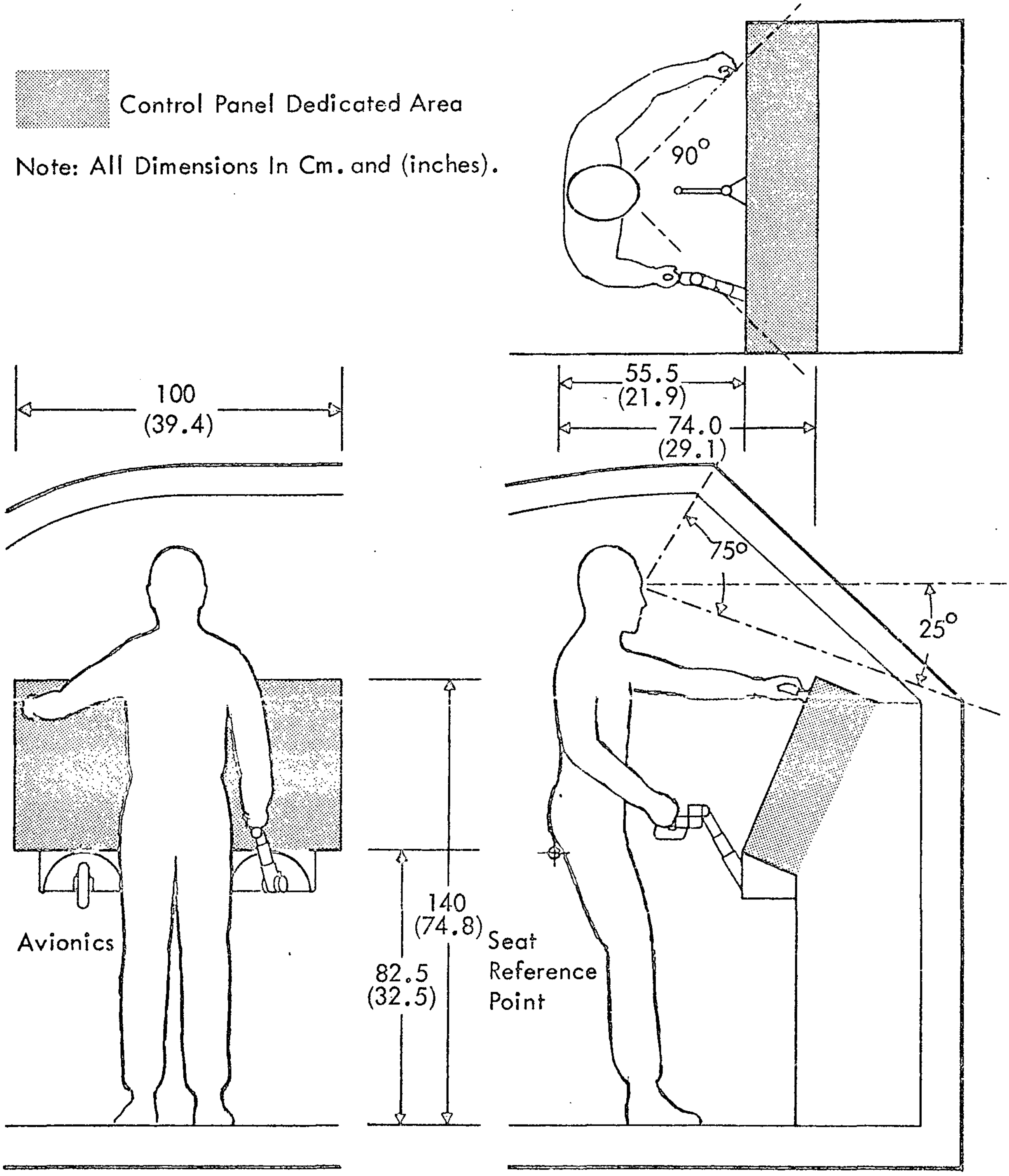


FIGURE 2.3-5
MASTER CONTROLLER USED FOR DEXTEROUS
END EFFECTOR CONTROL

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

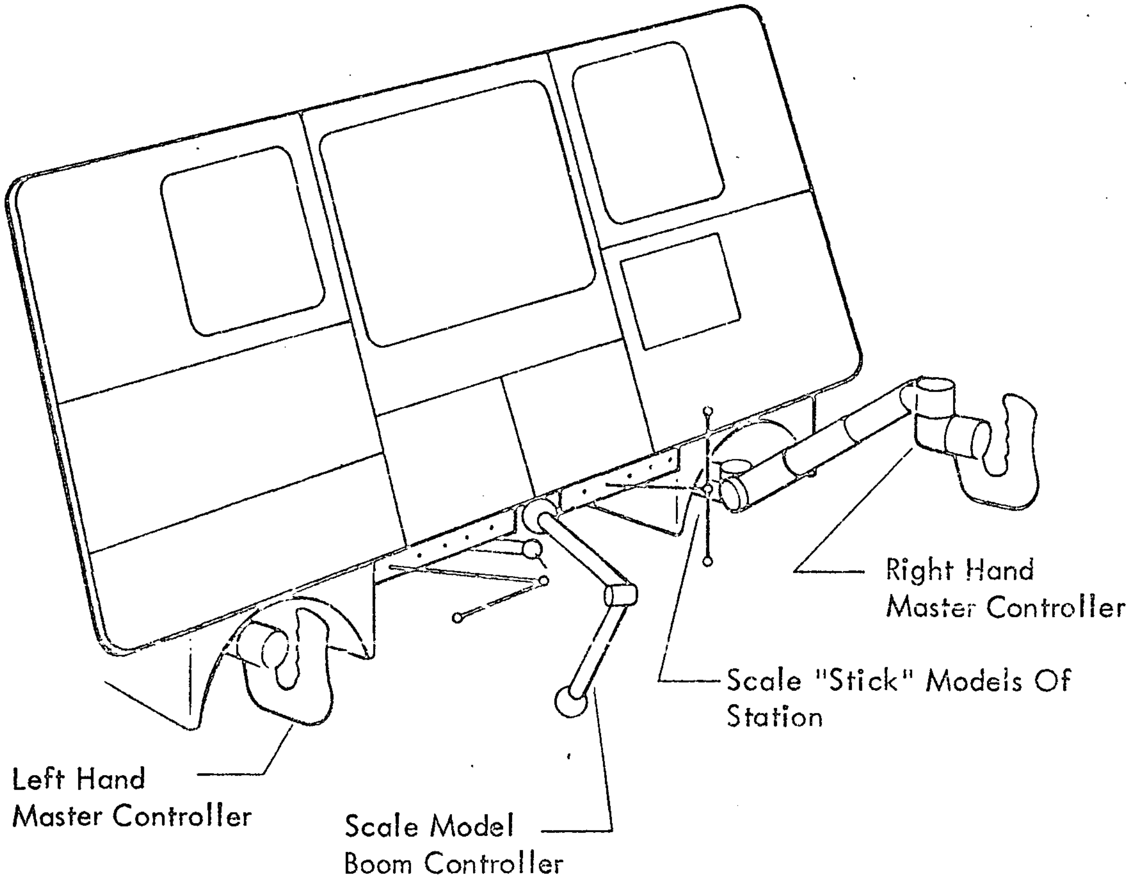


FIGURE 2.3-6.
LAYOUT OF MANIPULATOR CONTROLLERS

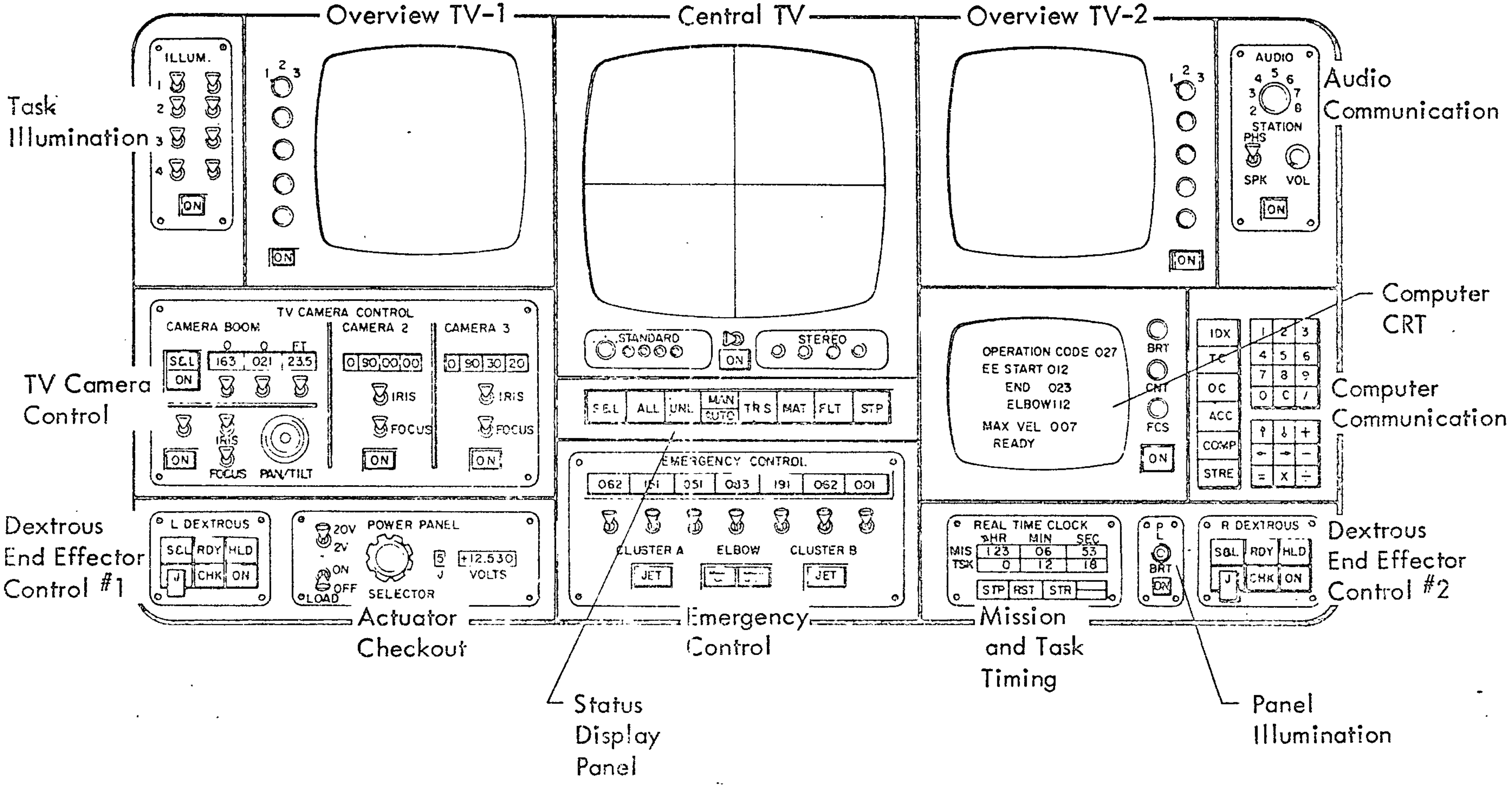


FIGURE 2.3-7
MANIPULATOR CONTROL PANEL LAYOUT

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 Section 3. 2. 3 "Boom and End Effector Controllers" below and 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 2.4-1 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 ~ 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 2.4-1

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 in Section 3.0 "Results".

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).

It is important to emphasize that full and proper utilization of a space manipulator system requires that the satellites, space stations and other vehicles to be served by the manipulator must be designed for such service. Thus, locking devices, fittings and components to be handled along with the tasks, or operations required, should be designed for manipulator handling at their inception. Such an approach will enable achievment of the full potential of space manipulator/teleoperator capability by minimizing task time and difficulty and also the hazards and frustrations of loss of tools, fittings, bolts, etc., by "floating" away will be minimized (and in fact should be eliminated).

Specific manipulator operations, end effectors and auxiliary devices for station assembly and maintenance and LST servicing are presented in Section 3.0 "Results". Additional considerations of Utility, including possible shuttle root point locations and viewing windows, are presented in Section 6.0 "Technical Discussion".

2.5 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 boomsas 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.

2.6 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 may be acceptable for meteoroid module deployment and retrieval and only a modest (single field monocular) TV system may be required 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.

3.0 RESULTS

The information presented in this section backs up the key features of the manipulator system concept analysis described in Section 2.0 "Summary". Additional and more detailed information is presented in Section 6.0 "Technical Discussion". Section 3.0 is broken down into seven subsections: 3.1 - Boom Design and Analysis; 3.2 - Man/Machine Interface; 3.3 - Viewing System; 3.4 - Boom Control System; 3.5 - Utility; 3.6 - Reliability; and 3.7 - Safety. The reader is referred to the Table of Contents for a breakdown of Section 6.0.

3.1 Boom Design and Analysis

3.1.1 Actuators

The boom actuator configurations were not established in Phase I "Concepts Development and Selection" because they were considered of secondary importance relative to selecting an overall manipulator system concept. In other words, the overall boom configuration was allowed to dictate the actuator envelope and performance requirements since it was believed that the actuators could always be made to fit the desired boom constraints. A detailed comparison of all of the actuators considered in the concept analysis phase is presented in the technical discussion, Section 6.3.3 "Actuator Configurations". A brief review of the actuators considered and important facets of the selected Double Differential Gear Actuator are discussed in the present section.

The actuator envelopes must be compatible with the MSC specified 22.9cm (9") diameter boom envelope and with the design rule requirements for close coupled orthogonal locator (shoulder)/orientor (wrist) assemblies (see Section 6.3.1 "Kinematics and Joint Configuration" and Volume II "Concept Analysis").

The required range of motion for each actuator is shown in Figure 2.3-3. The approach used was to select a single actuator configuration which could meet all of the above requirements. In addition, the following design criteria was used.

(1) Lightweight - the actuator should produce the largest load capability within the total weight budget.

(2) Overload protection - the actuator should be capable of "slipping" when loaded just above full load rating to provide protection against internally or externally imposed overloads. The actuator should not require "re-setting" after slipping.

(3) Reliability - all actuators considered had dual drive motors for redundancy. An operator actuated declutch is required to free the joint from a disabled motor or drive train assembly. The gearing was assumed to be reliable (i.e., no credible failures).

(4) Free play (backlash) - to be zero or minimized.

(5) Oil/Fluid Leakage - actuator oil or working fluid leakage should be minimal (~zero) to prevent possible contamination of optical lens, coatings, etc.

(6) Efficiency - some consideration was given to efficiency because of the limited power available (particularly on the shuttle).

A variety of electric drive motors was considered and on the basis of state-of-the-art, high efficiency, small size and weight, ease of control and compatibility with station and shuttle power, a shunt type DC motor was selected [efficiency ~74%, specific power ~.11 hp/Kg (.05 hp/lb) and speed ~5000 rpm]. Furthermore, the large speed control dynamic range (say 50/1) offered by a shunt type motor makes it possible to provide the range of joint speeds required for inverting the "wrist" and "shoulder" as is done in the walking boom concept; i.e., the wrist must move fast relative to the shoulder.

The following ten different types of DC electric motor driven actuators were considered:

(1) Spur Gear Train
(2) Serpentuator Compound Linkage
(3) Harmonic Drive
(4) Ball Screw/Linkage
(5) Hydraulic Cylinder/Linkage

(6) Hydraulic Cylinder/Silent Chain
(7) Cone Drive Gear
(8) Double Cone Drive Gear
(9) Internal Spin Gear
(10) Planocentric Double Differential Gear

The planocentric Double Differential Gear Actuator configuration was selected because of its:

(1) Compact size and low weight

(2) Compatibility in shape and range of motion for use in both pivot and roll joints.

(3) Redundant arrangement of two parallel motors and drive trains (reliability).

(4) Ability to eliminate backlash by stopping the double drive gear slightly out of phase (i.e., working against each other).

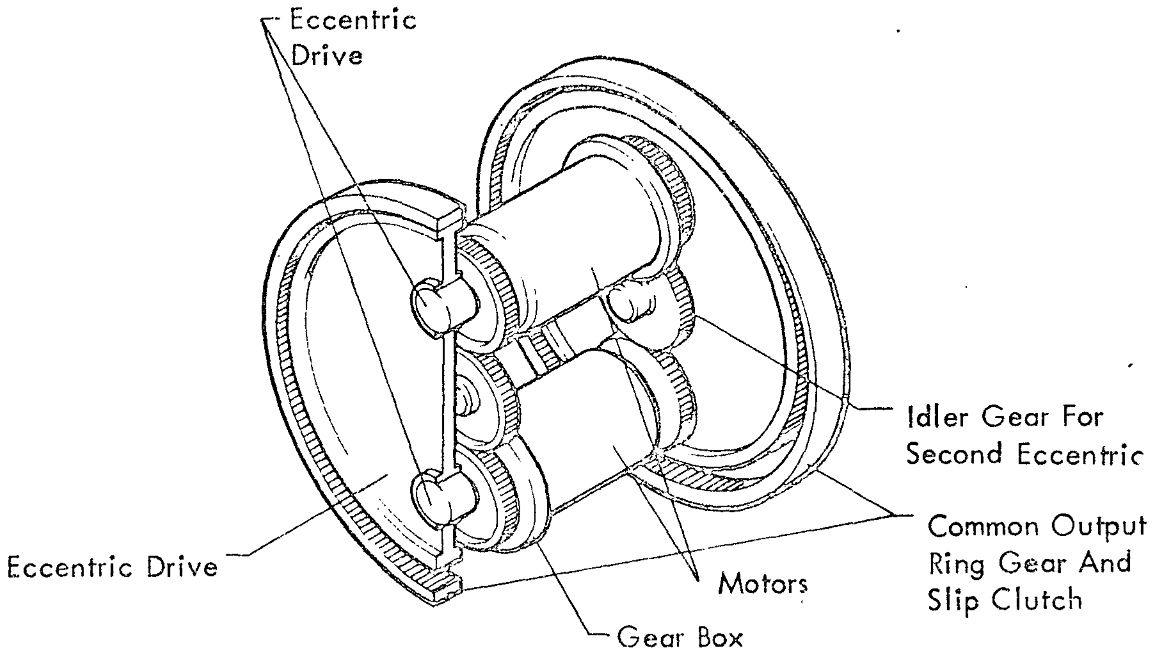
(5) Good overall efficiency (~70%).

(6) Hermetically sealed motor and high speed drive train (no oil leakage).

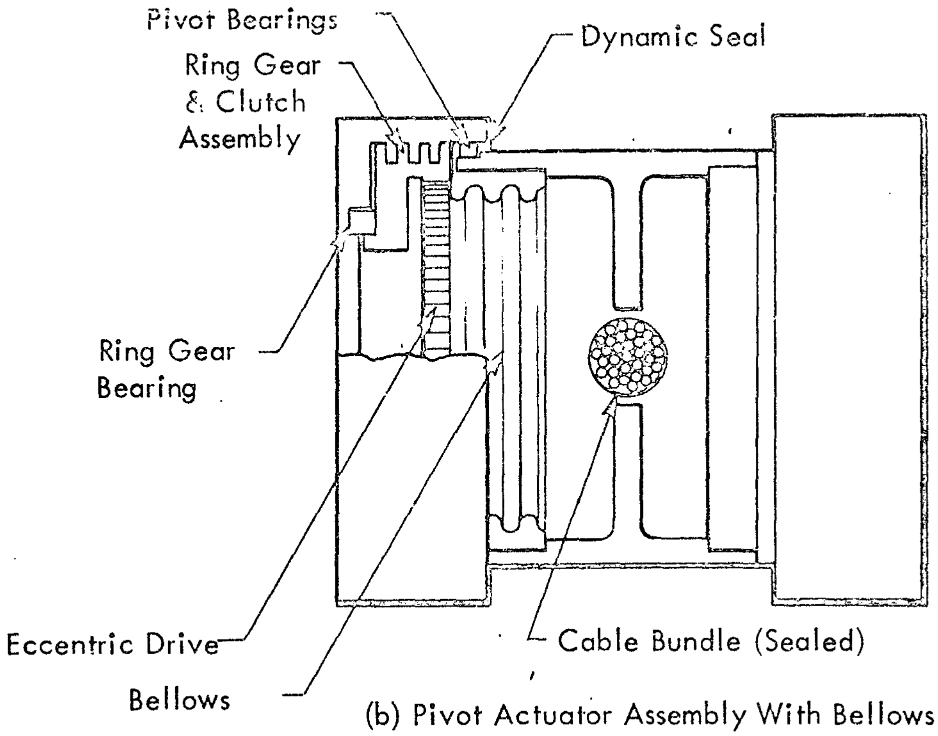
(7) Ability to separate the functions of the heavily loaded eccentric drive and of the flexible bellows seal.

(8) Reduced output gear tooth load achieved by ability to have wide teeth of ideal form and by spreading the load over many teeth.

A schematic arrangement of the Double Differential Gear Actuator configured for a pivot joint is shown in Figure 3.1-1. The motor and drive trains are arranged in mirror image fashion, each driving an output ring gear/cluth assembly on opposite sides of the joint. Figure 3.1-1(a) illustrates that way in which a bellows can be used to seal the eccentric drive to the inner cage assembly which houses the drive motors, high speed gear reducer and the actuator thermal and speed control components (see Drawing 0053ES0692). The joint cable pass throughs are sealed to complete the hermetic seal of the inner cage. The only working parts exposed to vacuum are the joint bearings and the ring gear/clutch assembly. Since these are located at the maximum diameter of the joint, the loads they experience are minimized. For example, the average maximum bearing/



(a) Double Differential Gear Train



(b) Pivot Actuator Assembly With Bellows And Dynamic Seals

FIGURE 3.1-1.
SCHEMATIC OF DOUBLE DIFFERENTIAL GEAR
PIVOT ACTUATOR

load (force/diameter) is about 6.9×10^4 N/M^2 ($\sim10^3$ psi) and the gear teeth loads are low enough so that aluminum alloy gears can be used (the eccentric and ring gear can be designed to spread the load over many teeth). Thus since the joint rotational velocities are low (2-10°/sec) and the loads are not extreme, available hard vacuum space lubricants may be acceptable. A dynamic seal can be incorporated (see Figure 3.1-1(a) to increase the vapor pressure on the "exposed lubricants." If difficulties are encountered with lubrication of the gears, bearings and clutches (it is necessary to prevent the clutches from vacuum welding) an elbow type bellows seal can be placed over the entire joint as is done on the MSFC Serpentuator boom. A complete hermetic seal could be achieved in this manner permitting use of a controlled atmosphere and conventional lubricants throughout the joint.

A schematic of the Double Differential Gear actuator configured for a roll joint is shown in Figure 3.1-2. In order to use the double gear drive feature (ability to achieve zero backlash), both output drives must be on the same end since ± 180° of rotation are required. In the arrangement shown, both motors force the same way, but they are 90° apart and the second motor/drive assembly passes through the eccentric drive of the first motor/drive assembly. Since there is only one output ring gear, the slip clutch on it can only be used for overload protection. Separate clutch assemblies are required on each motor drive unit to isolate it in the event of motor failure. A bellows seal is attached between the first eccentric drive and the inner cage and a second bellows seal is attached between the two eccentric drives. The second bellows allows the two drives to be shifted out of phase by the amount of gear backlash in order to eliminate the effective backlash. The inner cage is lengthened somewhat to provide adequate separation of the joint bearings. The wiring passing through the joint must be routed differently than for the pivot joint, but since the inner cage is longer, there is adequate room to coil the wire to allow flexing for the ±180° rotation. A dynamic seal is incorporated to minimize outgassing of the bearing, gear and clutch lubricants. If lubrication problems are encountered, it is not as easy to hermetically seal

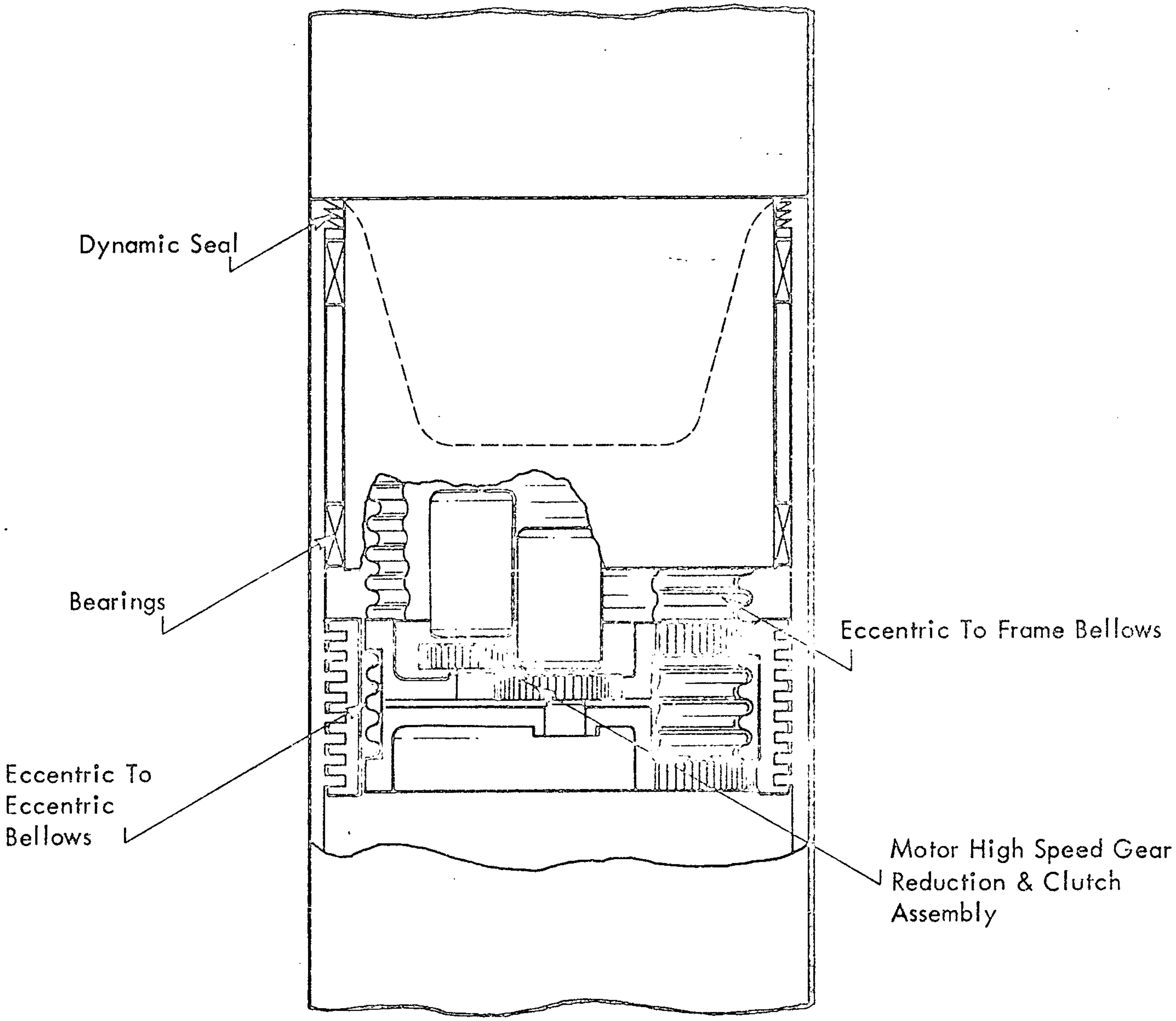


FIGURE 3.1-2.
SCHEMATIC OF DOUBLE DIFFENENTIAL ROLL ACTUATOR

the roll joint as it is the pivot joint. A loose fitting stretchable elastic boot could be used, but undoubtedly it would require periodic maintenance or replacement.

Lubrication of the output gear/clutch assembly and joint bearings should not be a problem for shuttle based manipulator operation since the shuttle is only in orbit a short time and ground based joint maintenance can be employed. Shuttle logistics costs prohibited frequent ground based maintenance for space station manipulator operations. Thus either joint lubrication must be demonstrated not to be a problem or a means of providing effective maintenance on the station must be provided. By proper design it is possible to accomplish a station replacement of a manipulator roll joint boot by inserting the roll joint into an air lock through a sealed mechanical locking type fitting. Station personnel could then replace a boot in a shirt sleeve environment. Pivot joint maintenance would not be required because a metallic elbow type bellows could be used if required.

3.1.2 Root Point and End Connector

The reference root point and end connector preliminary designs are shown in Figure 2.3-4 and 3.1-3. The root point and end connector assemblies have three (3) functions: (1) to provide mutual radial and axial mechanical alignment, (2) to provide structural attachment of the boom and (3) to provide electrical contact of all the power, command, monitor and video circuits.

Axial alignment is provided by making the root socket approximately 1/2 diameter deep, by maintaining close diametral tolerances between the boom tip and root socket and by maintaining perpendicularity and flatness of the seating faces. The diametral clearance must be sized to preclude interference or a "tight fit" condition throughout the operating temperature range of the assembly. As shown in Figure 3.1-3, radial alignment is achieved by 3 non-symmetrically arranged keys (on the end connector) and keyways (on the root point). Circumferential clearance between keys and key ways can be held to within $\sim 5 \times 10^{-2}$ mm (2×10^{-1} inches) so that radial alignment can be maintained to within about 3×10^{-2} degrees. The keyways would be chamfered at the top to allow easy initial alignment of the boom.

Structural attachment is achieved by use of a quick turn, breech block type assembly. The breech block collar is driven by a hermetically sealed motor (a harmonic drive unit for example) between open and closed stops. Hermetically sealed micro switches (or a recessed pin/socket assembly) are used to indicate the status of the breech block collar and proper seating of the boom tip. When the limit switches (3) indicate that the boom end is fully inserted, the breech collar would be rotated to the closed position. The breech collar and seating faces provide structural support against bending moments. The radial alignment keys and keyway, provide structural support against torsion loads. The bearing and tooth loads are not high [on the order of $3.44 \times 10^6 N/m^2$ (500 psi) for the reference 111 N (25 lb) tip force] so that available space qualified lubricants should be satisfactory for all sliding mechanical interfaces.

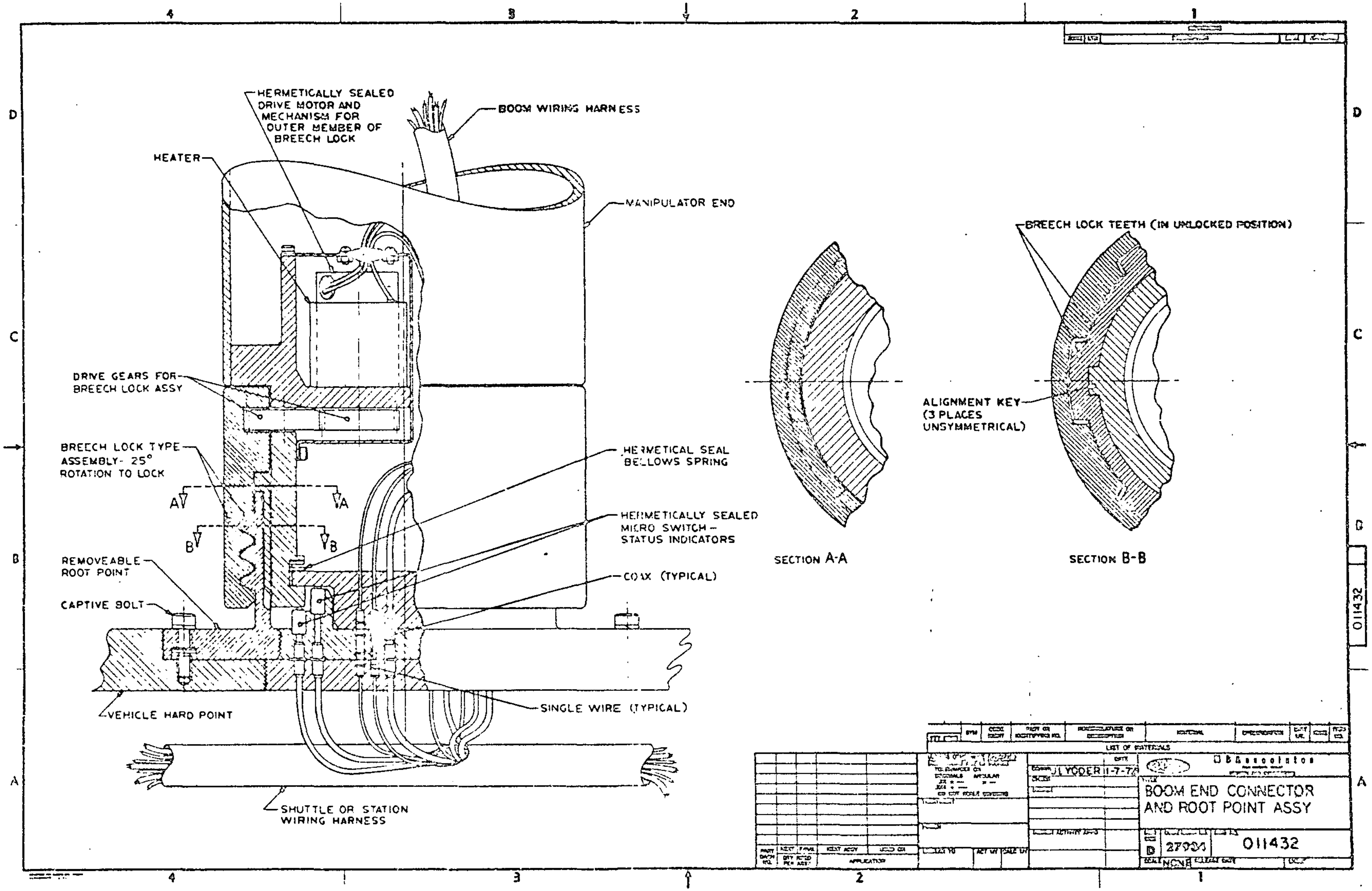


FIGURE 3.1-3
REFERENCE END CONNECTOR/ROOT POINT CONFIGURATION

A removable root point configuration was selected for the reference design to permit replacement in the event of wear, damage or upgrading of the unit. The root point can be removed by use of a special end effector on the boom. The end effector would attach to the root point (mechanically only) in the normal manner and at the same time would engage drive heads into the captured bolts. Alignment pins on the root point/vehicle interface would provide alignment of the new unit. The end effector could also be designed to provide alignment (axial alignment for example).

A secondary alignment flange is shown for mating the electrical connectors. The boom electrical interface is allowed to "float" by use of the spring bellows so that fine misalignments relative to the electrical connector can be compensated for when the boom interface slides into the root point female receptacle. Conventional pin/socket electrical connectors are shown since these are the only type that have been qualified for space. This type is acceptable for the root point/vehicle interface since the root point will only be removed infrequently. However, wear may become a problem at the boom/root point interface. Current space qualified connectors are required to function after 500 connects/disconnects, but this is done in normal atmosphere. It is of interest to note that the Deutsch Connector Company has a side loaded leaf spring pin/socket connector that has sustained documented cycling 5 x 10^3 times, and it has been company cycled (without documentation) to almost 10^6 cycles. There is little experience on vacuum cycling electrical connectors but on the basis of the above and available space materials technology, it would appear that an acceptable unit can be developed. If wear proves to be a problem, butt-end spring loaded type contacts could be used. (See Section 6. 3. 7)

2 (7)

3.1.3 Weight, Material and Deflection Trade Offs

There was no firm criteria on either task time or maximum tip force level. Completion of tasks or major elements of them within a half orbit period was used as a ground rule to minimize variations in lighting conditions. Some task times are determined by the nature of the task such as shuttle capture which is dictated by separation distance and the relative closure velocity. Other conditions aside, it is desirable to be able to complete tasks quickly, to have the highest possible tip force capability for contingencies and to have minimum deflection to make spotting, mating, etc. as easy as possible.

The boom is deflection limited rather than stress limited because of its large length to diameter ratio ($\sim$80/1). Thus stiffness to density rather than strength to density is the dominant criteria in selecting a boom material. Composite materials offer high stiffness to density ratio potential but because of their relatively undeveloped state-of-the-art they were ruled out by NASA, MSC. Light weight metals of interest are compared in Table 3.1-1 where a thin walled, constant section circular tube is used as a reference boom shape. If one specifies that the shape is constant (same thickness, diameter and length) then it is seen that Be and Mg offer a weight advantage over Al. However, because of its lower modulous (E) Mg results in larger deflections and is therefore not desirable. It is of more interest to specify the same deflection, diameter and length and compare the weight, thickness and tip force. Since the tip force (bending moment) is proportional to $t\,\sigma_B$ (see Table 3.1-1) the forces are the same for all materials since the diameter is constant. Thus since the deflection and tip force are the same, we have a valid comparison of boom weight. Now it is seen that an Al tube is lighter than a Ti tube, therefore the choice is between Al and Be. If the fabrication technology and fatigue/crack sensitivity of Be were equal to that of Al, Be would be the obvious choice. However such is not the case. Be is typically used in either very short life time applications (missiles) or in low stress situations. The present application is one of low stress [$\approx 6.9 \times 10^7$ N/m^2 (10^4 psi) for Be for the

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

					Same (t, r, ℓ, σ_B)		Same (ζ, r, ℓ)			
Material	E (lb/in^2)	ρ (lb/in^3)	σ_{Tu} (lb/in^2)	σ_{Ty} (lb/in^2)	(ζ/ζ_{Al})	$\left(\frac{wt}{wt_{Al}}\right)$	$\left(\frac{t}{t_{Al}}\right)$	$\left(\frac{\sigma}{\sigma_{Al}}\right)$	$\left(\frac{wt}{wt_{Al}}\right)$	$\frac{F_{tip}}{F_{tip}Al}$
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	$*70 \times 10^3$	$*50 \times 10^3$	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 3.1-1
BOOM MATERIAL COMPARISONS

geometry assumed in Table 3.1-1], thus Be is of interest. However, Be tubing is not available in the sizes required; therefore either new fabrication tooling/techniques must be developed or a skin frame and rivet type structure must be used. In the latter case experience indicates that such Be structure can be built for approximately half the weight of an equivalent Al structure. There also are Be alloys under development (such as Lockheed's Lockalloy which is ~1/3 Al) which offer better ductility and lower crack sensitivity than pure Be. The use of Be or its alloys is very dependent on details of the actual design (total amount of material required to accommodate available forms, stress levels, etc.) and on the mechanical and physical properties of the material (density, crack sensitivity, stress working, etc.). Until such detail design studies (backed up with tests and experiments where required) are accomplished, Al has been selected as the reference manipulator structural material.

Figure 3.1-4 shows the task time required to linearly translate a 11,350 Kg (25,000 lb) cargo module (a distance of ~22.8 (75'). Constant acceleration and deceleration (constant tip force) are used and the maximum velocity is that for which the module can be stopped in 3m (~10'). That is the ability to stop the module within the field-of-view of a camera [assumed to be 3m' (10')] was used as a reasonable ground rule. For even the smallest tip force considered [44N (10 lbs)] it is seen that the task time is quite acceptable. Thus translation tasks are not a tip force design driver. Latching, unlatching, freeing a stuck module, berthing, etc. are potential design drives but they are undeterminant, at least at this time.

A weight limit of 454 Kg (1000 lbs) was specified as a study ground rule. The approach taken in selecting the maximum boom tip force/deflection was to estimate the weight of all components but the boom tubes and then to use the balance for the tubes. A weight/tip force summary is presented in Table 3.1-2. The weight of the dedicated boom, control system, TV system and control console are invariant with tip force. All other weights are dependent upon tip force. The weight available for the tubes as a function of tip force shows that there is an optimum (but difficult to define) force level since the higher the assumed force the less weight

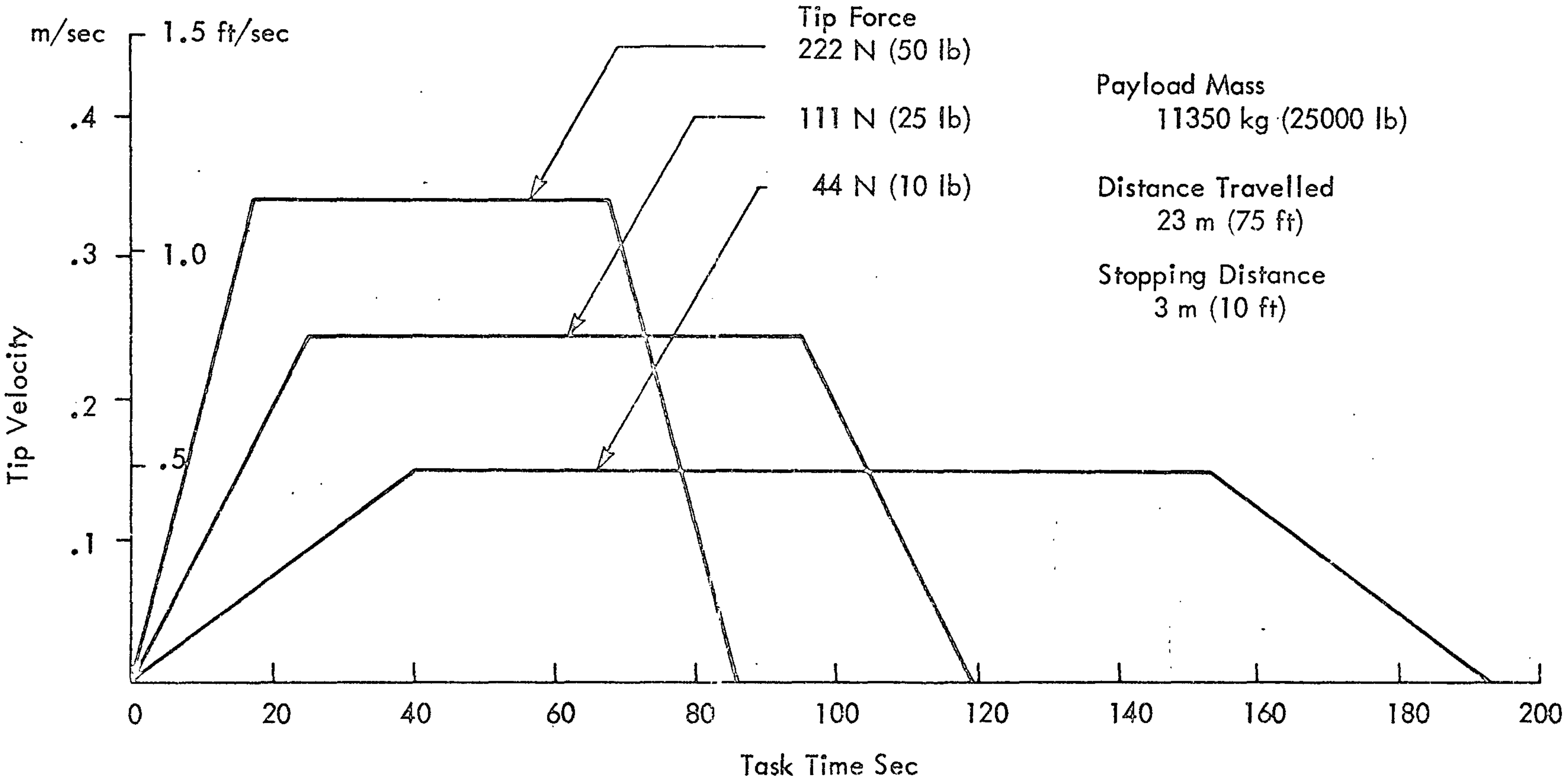


FIGURE 3.1-4
TASK TIME VS MAX VELOCITY FOR DIFFERENT TIP FORCES

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 3.1-2
SUMMARY OF MANIPULATOR SYSTEM WEIGHT VS TIP FORCE

available for the tubes. A 111 N (25 lb) force appears as a reasonable compromise and was selected for the reference design. Figure 3.1-5 shows the stopping distance required as a function of velocity for a 111 N (25 lb) force for the manipulator payloads of interest. The specified design driver [11,350 Kg (25,000 lbs)] can be stopped within 3 m (~10') from a velocity of ~1 fps and a large shuttle [113,500 Kg (250,000 lbs)] can be stopped within 10 m (~30') from ~.12 m/sec (.4 fps). This would only be done in an emergency since it is planned to use the shuttle ACS/ propulsion system to reduce the closure velocity to .03 m/sec (0.1 fps). Furthermore a smaller shuttle 68,000 Kg (150,000 lbs) will be used which could be stopped in ~6 m (18') from ~0.12 m/sec (0.4 fps).

Curves of deflection, stress and weight as a function of boom radius are presented in Figure 3.1-6. It is obvious that to minimize deflection the boom diameter should be made as large as possible (assuming wall thickness and boom size are reasonable) - thus the maximum allowed diameter of 22.9 cm (9") was selected. At this radius, deflection is reduced as wall thickness is increased and the reduction becomes progressively smaller as thickness approaches 5 mm (~0.2 in). Selection of the maximum allowable deflection equal to the shuttle berthing centerline miss distance [± 15.24 cm (± 6")] was taken as a boom design ground rule to resolve the thickness, weight, deflection trade off. A thickness of 4.8 mm (0.19 in) was therefore selected which resulted in a deflection of 14.2 cm (5.6") and a net boom weight of 142 Kg (315 lbs) not including actuators, end connectors, power system and clutches. The actuators and end connectors are capable of a 222 N (50 lb) tip force and since the tubes stresses at 111 N (25 lbs) are low the entire boom can operate at 222 N (50 lbs). However, the deflection would double to ± 28.4 cm (11.2"). This "extra" force capability provides a margin for contingencies.

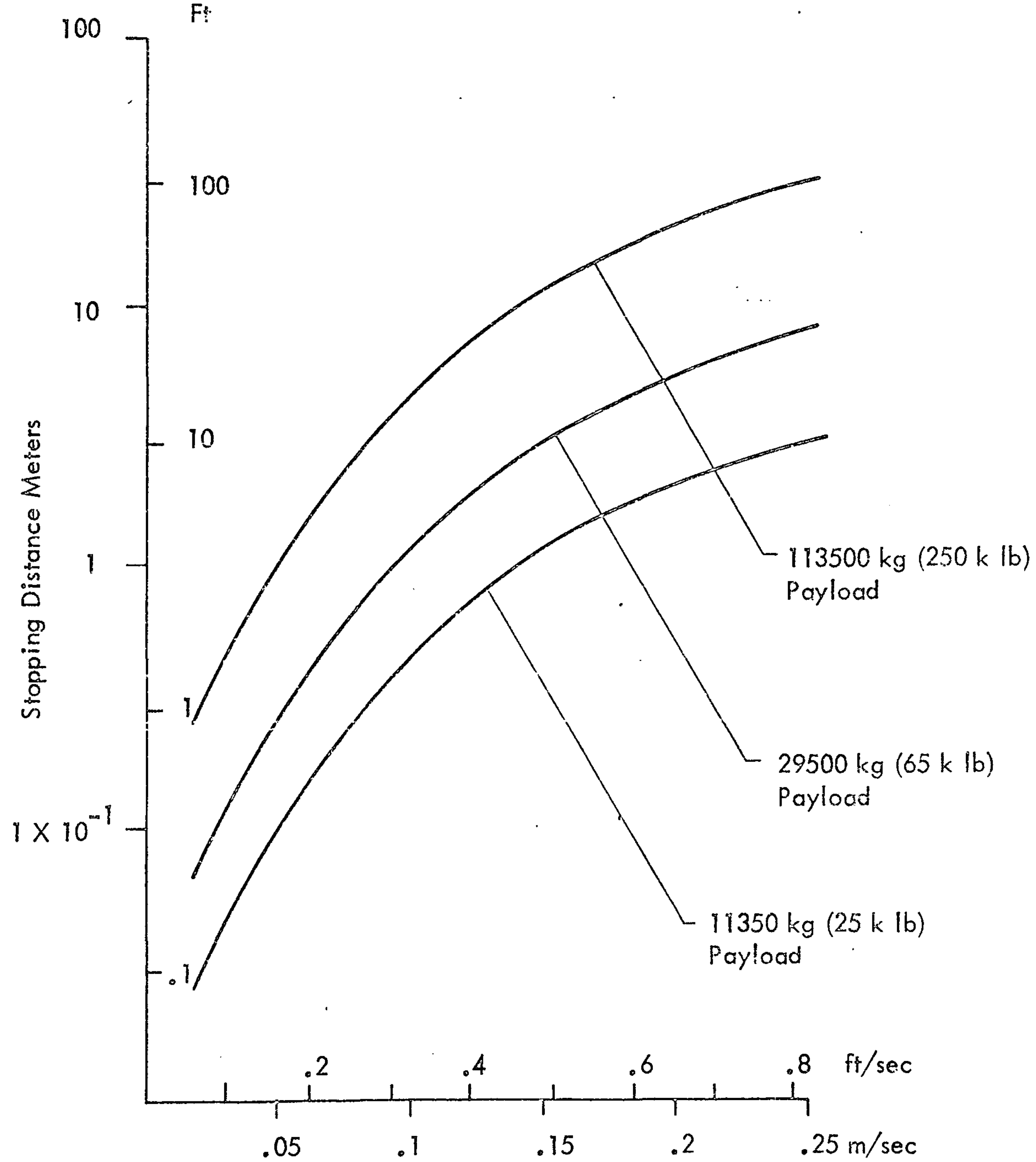


FIGURE 3.1-5
STOPPING DISTANCE FOR
111 N (25 Lb) TIP FORCE

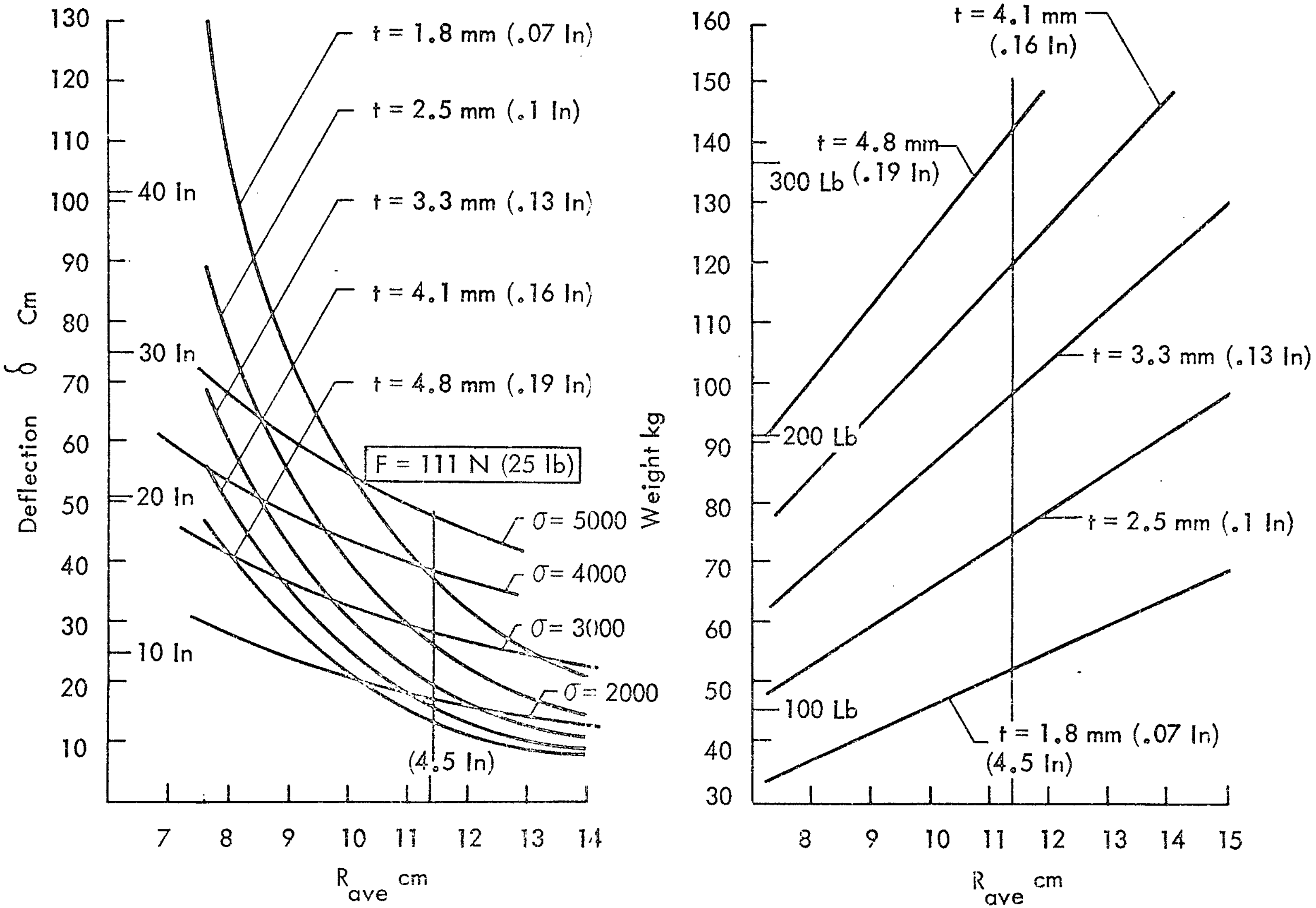


FIGURE 3.1-6
DEFLECTION AND WEIGHT TRADE OFF CURVES FOR AN ALUMINUM BOOM

3.1.4 Dynamics, Power Requirements and Thermal Analysis

3.1.4.1 Dynamics

No detailed dynamic analyses were accomplished, however, salient features of the boom dynamics were identified by simplified analyses considering the boom as a rigid cantilever beam with payloads of interest attached at the tip. The results are valid so long as the force levels involved are within the set actuator limits. When these limits are exceeded the boom becomes non-linear, however, it is in a "fail safe" mode since the actuators will dissipate energy as they are caused to slip. It is therefore difficult to damage the boom because it will not support "excess loads". The exception to this is when the boom is axially loaded when extended straight out.

The fundamental approximate vibration period characteristics of the boom are summarized in Table 3.1-3. Even without a load attached the cantilever bending period is large (2 secs) and for the 11,350 Kg (25,000 lb) design driver it is 23 secs. The fundamental torsional period for unloaded boom is small (.04 secs) as would be expected but with the design driver attached it also becomes large (8 secs).

The boom structure (Al or Be) will not provide good vibration damping (they have low internal stress damping characteristics). It is therefore desirable to provide a means of actively damping the boom oscillations in order to simplify task procedures and reduce task time. The actuator response time is very short compared with the loaded boom response time (period). It is therefore practical to use the actuators to damp-out the boom vibrations by absorbing the energy stored in deflecting the boom. A harmonic approach to this technique was demonstrated experimentally and is discussed in Volume IV "Simulation Studies". With the harmonic approach the oscillation can be damped in about one period. By use of other non-linear approaches, even faster damping is possible.

TABLE 3.1-3

BOOM DYNAMICS AND THERMAL CHARACTERISTICS

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	

3.1.4.2 Power Requirements

The maximum output power requirement of 34 watts (.045 hp) per actuator was determined by the combined maximum tip force and maximum tip velocity with the boom extended straight out. An overall actuator efficiency of 25% was assumed thereby requiring a maximum input power of 136 watts (0.18 hp) per actuator. Not all of the joints will operate at maximum power simultaneously, in fact they probably will not normally all operate together even at part load. Furthermore individual joints will not always operate at maximum power. A maximum combined boom command, monitor, control and actuator power requirement of 1 Kw was assumed as a reasonable value. Since the boom is normally computer controlled the above power requirements can readily be held within the 1 Kw value. The boom cameras and lights were estimated to require an additional peak power of 1 Kw so that the total maximum power requirement for the boom is estimated to be ~2 Kw.

3.1.4.3 Thermal Analysis

Simplified thermal analyses were accomplished to establish the general thermal control requirements and thermal distortion characteristics of the boom. (See Section 6.3.6 "Component Layout and Thermal Control and Thermal Distortion".) By assuming black paint (absorptivity/emissivity = $\alpha/e = 1.04$), a 230 mile sun synchronous orbit and the sun always hitting the manipulator boom it was estimated that the average equilibrium temperature is about -26°C (-78°F). This is well below the maximum of ~200°C (392°F) allowed for electric motors, controls, etc. (Good engineering practice limits the maximum temperature to less than this.) In fact since the boom will be in earth shadow ~50% of the time in some missions, heaters will be required to maintain motors and other critical components at a reasonable operating temperature.

A "worst" case thermal distortion analysis was made to determine the maximum thermal distortion that could be expected if the boom were heated by solar radiation on one side only. As shown in Table 3.1-3 for a black painted surface a maximum tip deflection of about ± 35.6 cm (14") can occur with a time constant of ~5 minutes. (The ± deflection occurs if the boom is first heated on one side and then the other.) Distortions of this magnitude and rate are unacceptable for precise manipulator operations so that some form of overall thermal control is required. Table 3.1-3 shows the simple expedient of placing a thermal shield, crinkled, plated mylar for example, around the boom would reduce the maximum deflection to ± 3.6 cm (± 1.4") - an acceptable value. The time constant would also be increased by an order of magnitude to say ~50 minutes.

3.2 Man-Machine Interface

Details of the man-machine interface (the control console are presented in Section 6.4. Key features of the control modes, panel allocation and controllers are described below.

3.2.1 Functional Control Modes

Considerable study has been made of the man/machine interface and accordingly several controllers and control modes have been selected. The scale factor between man and the main boom (~20/1) the necessity to move large masses [11,350 Kg (25,000 lbs)] with small forces [111 N (25 lbs)] and the requirement to safely stop such masses within the field-of-view of the viewing cameras [(say 3 m (~10'))] makes it impractical to control the boom for gross translations (times of say 10 to 20 minutes) by a conventional master/slave teleoperator control system. In the selected control concept a single operator interfaces with a primary set of displays and controls at the control console. An on-board computer intervenes between the man-machine interface and the controlled system. The type and degree of intervention is a function of the system task. A schematic block diagram of the man-machine interface design concept is shown in Figure 3.2-1. Overall control has been broken down into 4 functional modes: (1) Translation control; (2) Mating and Berthing Control; (3) Dexterous Control and (4) Emergency Control. The control and feedback paths for each of these modes is illustrated in Figures 3.2-2, -3, -4 and -5 respectively. In the case of the emergency control mode it is assumed that the computer has malfunctioned so that the operator must directly control the boom by use of toggle switches, one for each actuator. The position and status of each actuator is displayed by a digital readout which bypasses the computer.

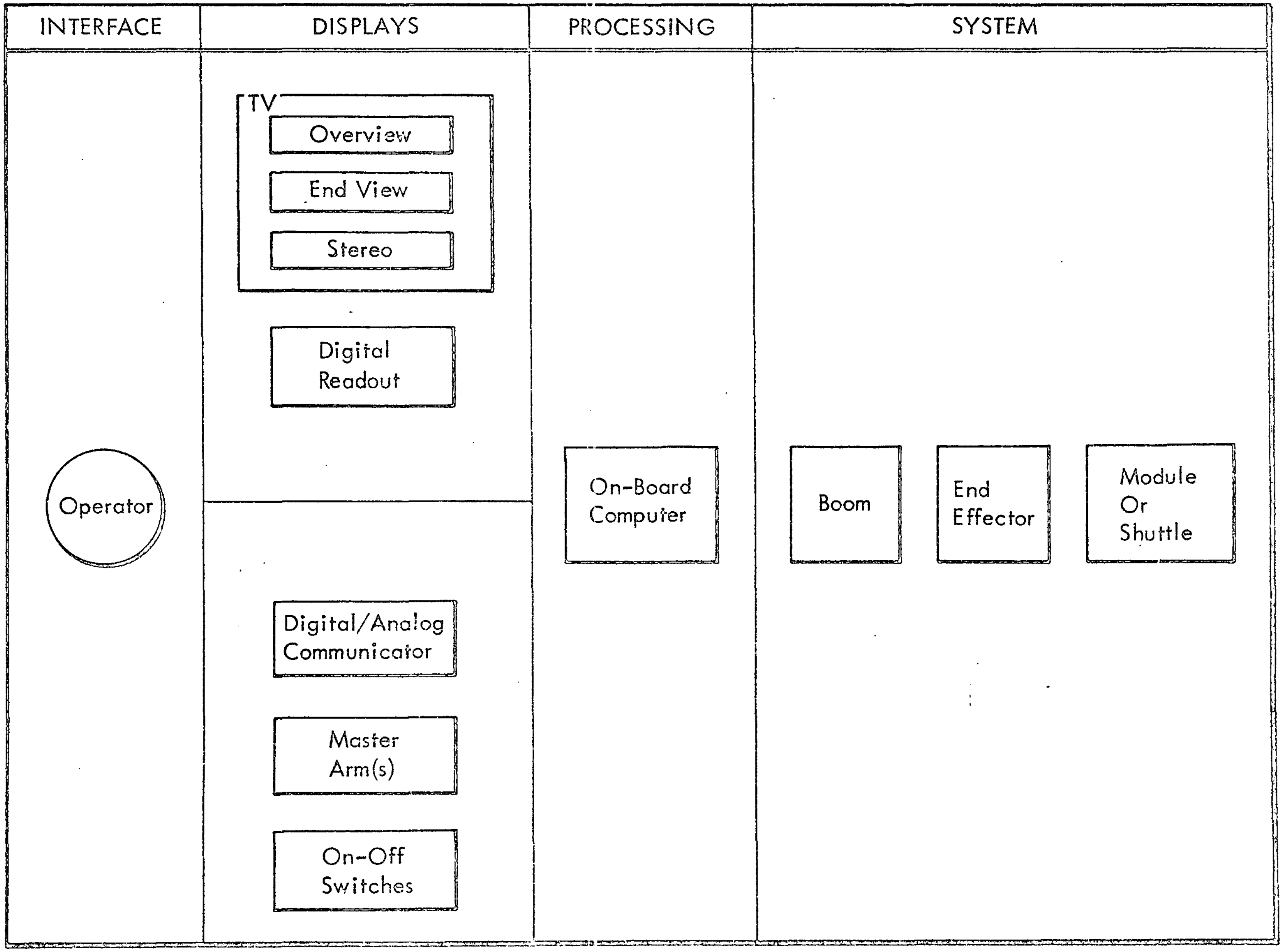


FIGURE 3.2.1
OPERATIONAL CORE OF SELECTED MAN-MACHINE
INTERFACE DESIGN CONCEPT

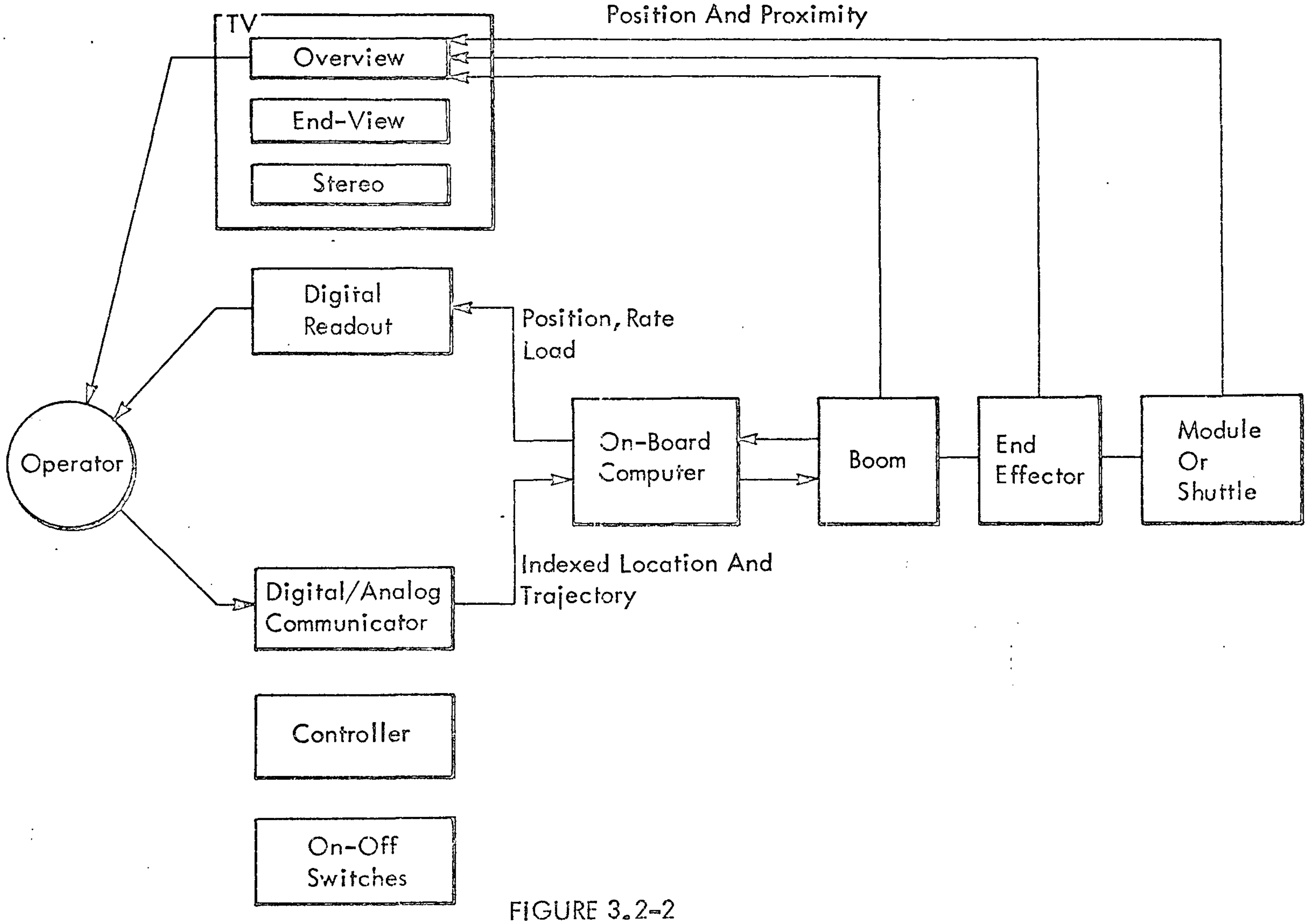


FIGURE 3.2-2
TRANSLATION CONTROL MODE

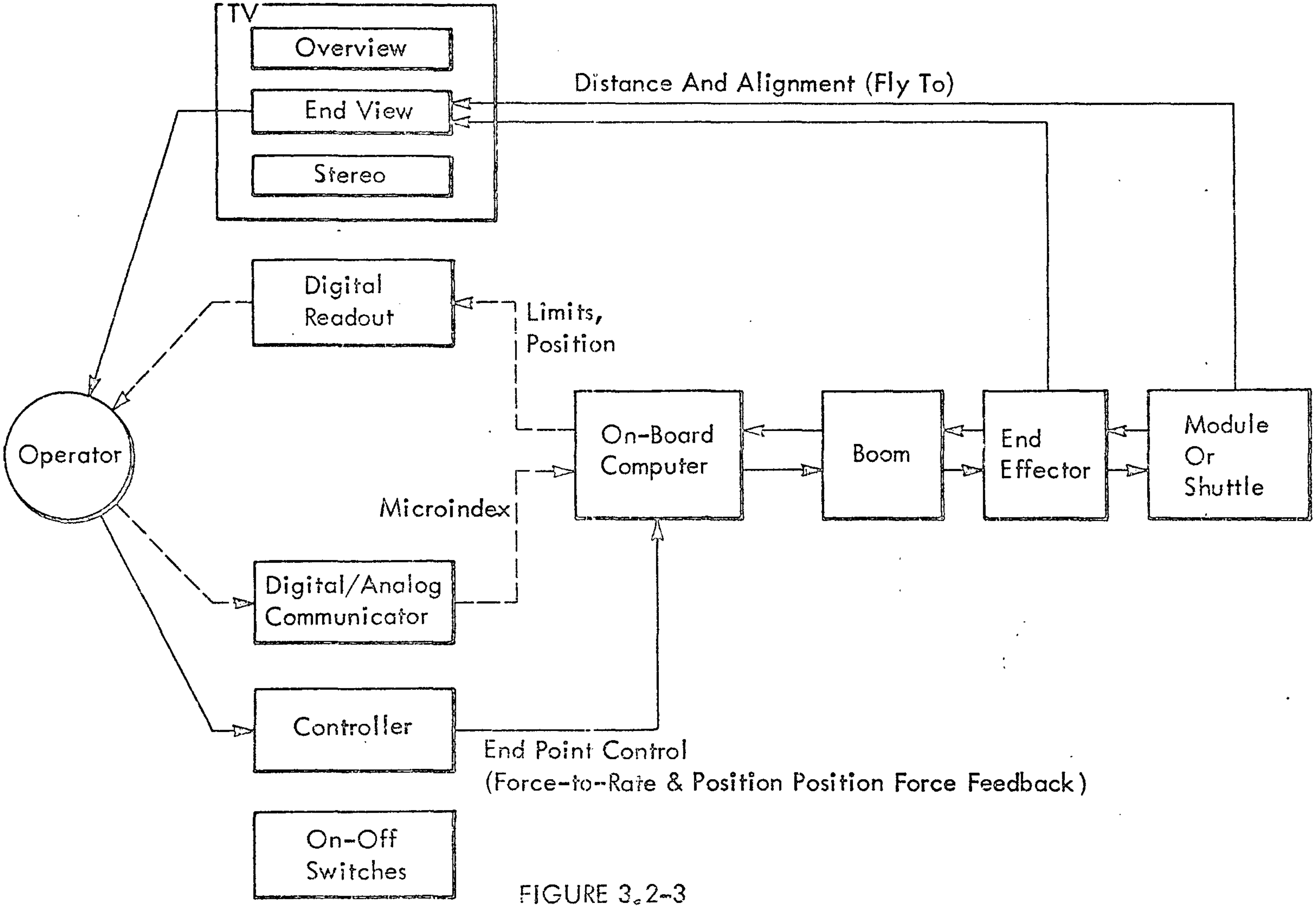


FIGURE 3.2-3
MATING AND BERTHING CONTROL MODES

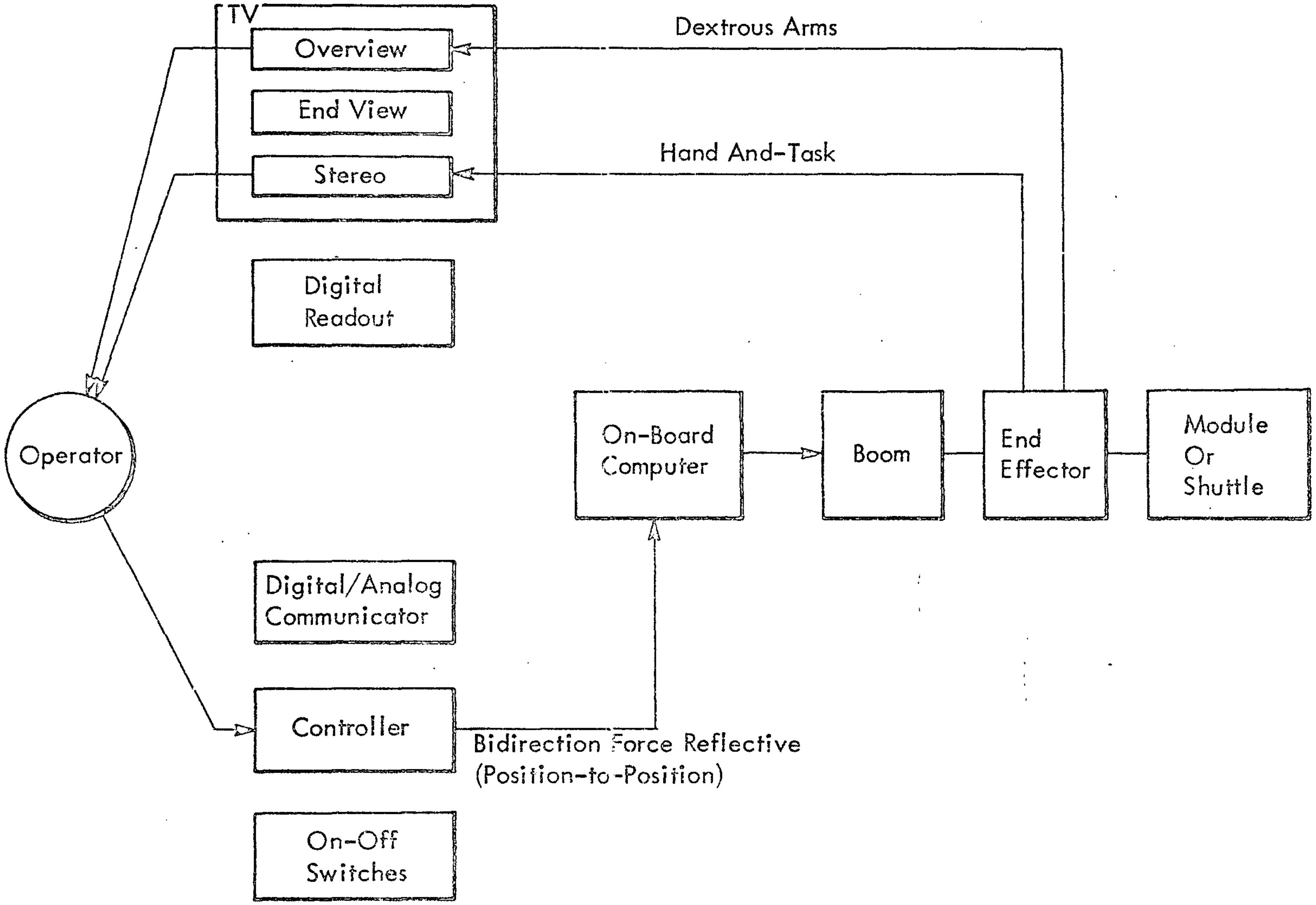


FIGURE 3.2-4
DEXTROUS CONTROL MODE

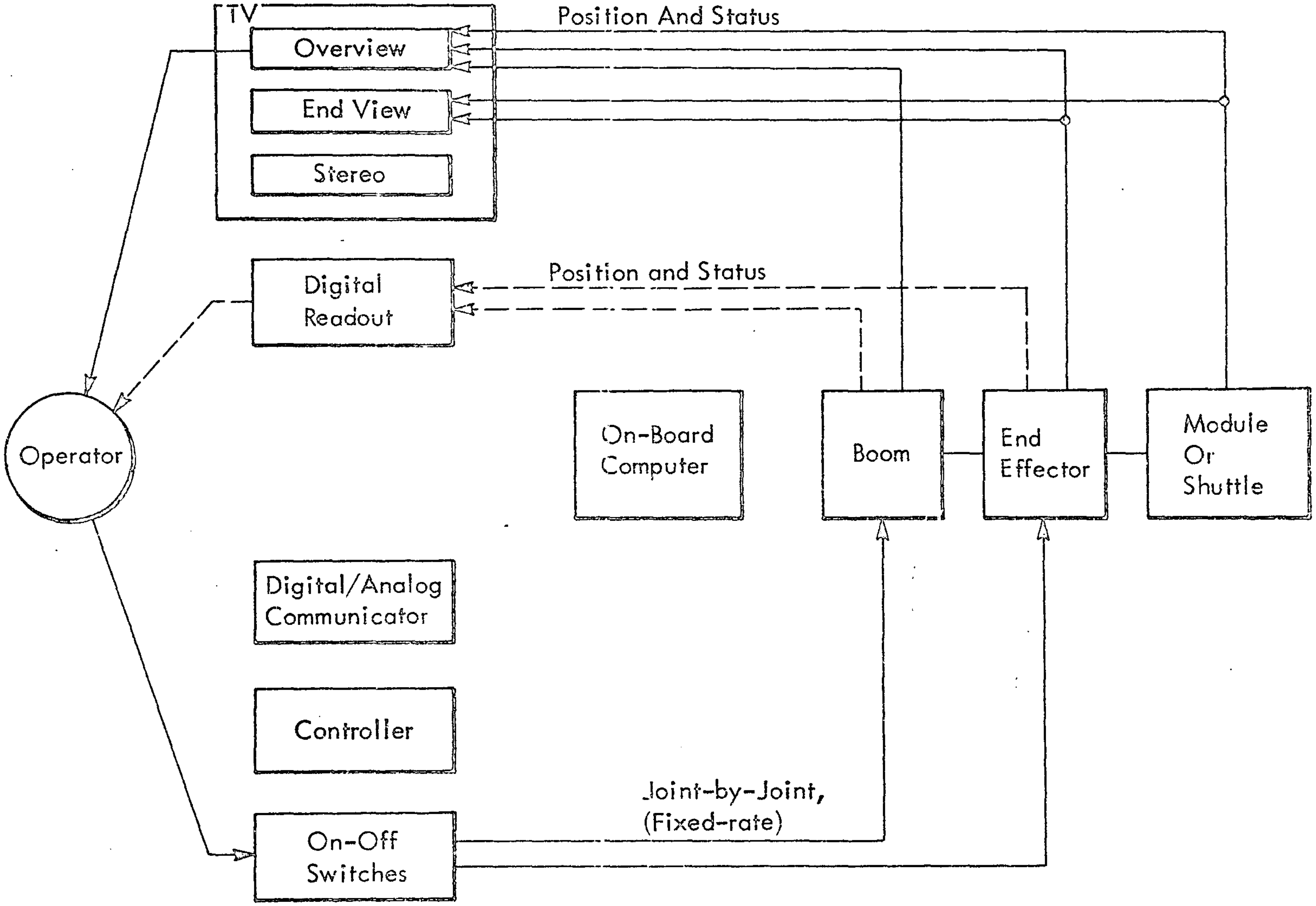


FIGURE 3.2-5
EMERGENCY BACKUP CONTROL MODE

3.2.2 Control Panel Functional Allocation

The overall control panel is shown in Figure 2.3-7. Details of the individual subpanels are presented in Section 6.4. The primary criteria used for optimum functional design of the operator's console were:

(1) Displays and controls which are functionally related should be grouped together.

(2) Displays and controls which are most important should be placed where they are easiest to see and reach.

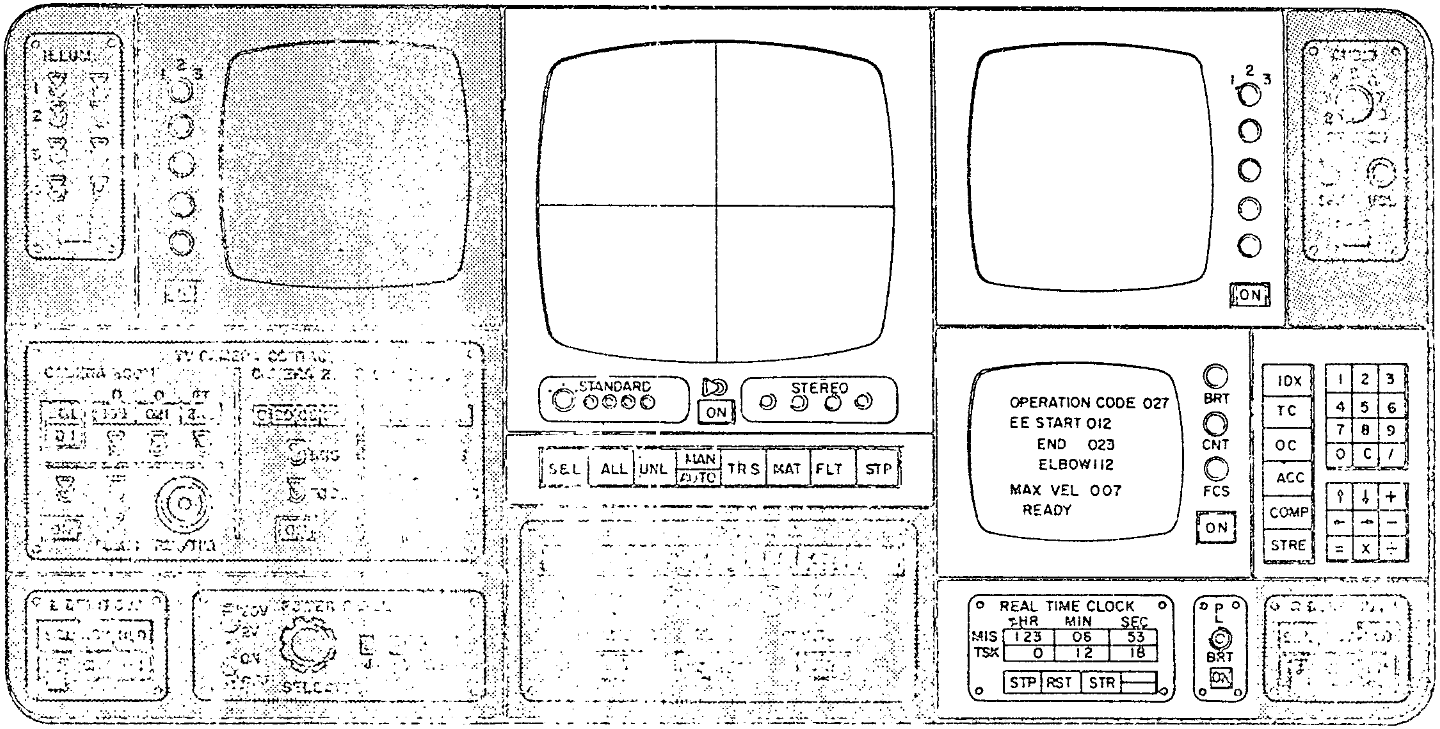
(3) Panel placement and configuration should meet the space requirements of the shuttle crew compartment since room there is more restricted than on the space station, and direct vision is a significant factor.

Figure 2.3-5 shows how the control console is arranged in the 040A shuttle crew compartment. The way in which the different functional areas of the control console are grouped together is illustrated in Figure 3.2-6, -7, -8, and -9, where the shaded areas black-out the groupings not used for each of the respective functional control modes described above.

3.2.3 Boom and End Effector Controllers

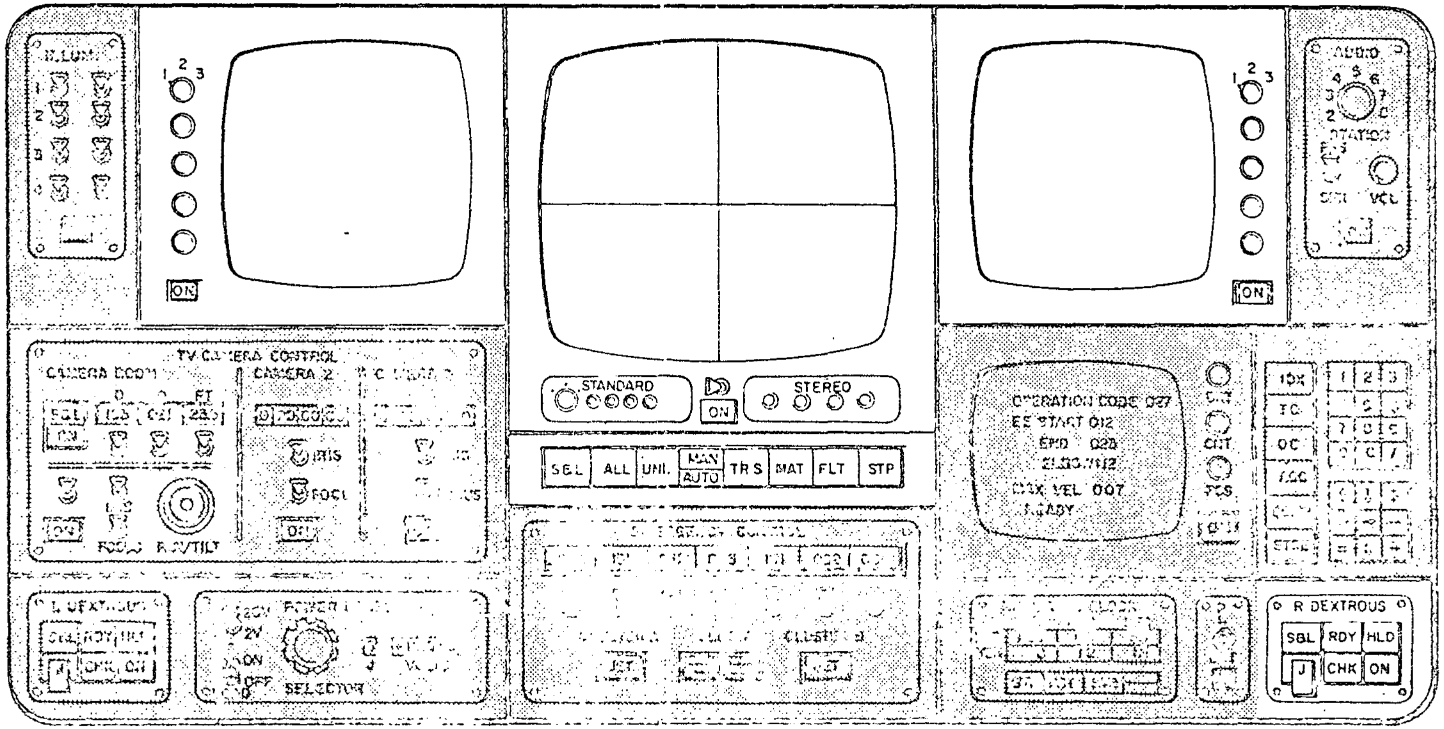
The location of the controllers is shown schematically in Figure 2.3-6. A detailed design of the controllers has not been made but the concept is well understood and their feasibility has been established by simulation studies.

The two 6 DOF controllers are used for end point rate control (positioning the end of the boom); combined end point rate plus orientor (wrist assembly) force reflecting position-position control [capture operations where the capture "socket" must be pursued



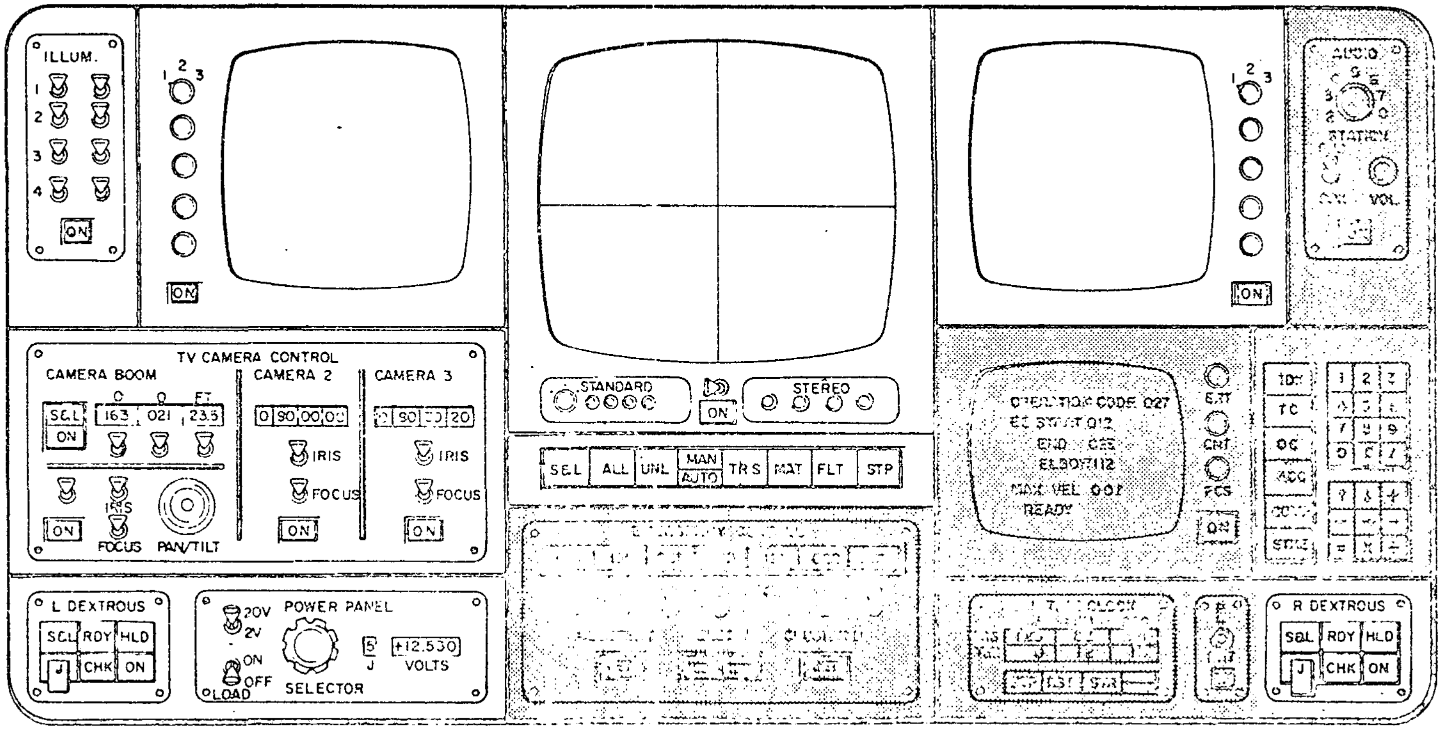
(Shaded Area Non-Primary)

FIGURE 3.2-6
PRIMARY PANEL AREAS USED IN TRANSLATION CONTROL



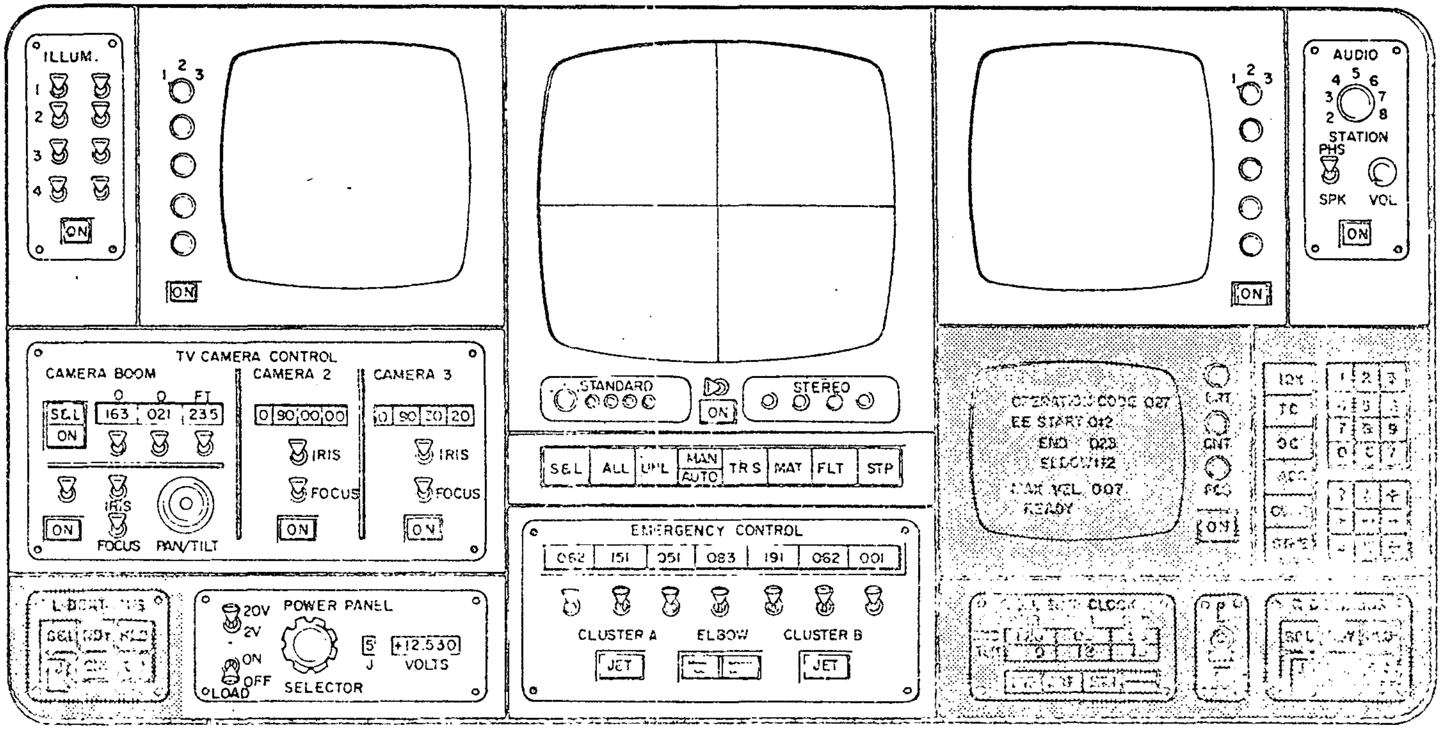
(Shaded Area Non-Primary)

FIGURE 3.2-7
PRIMARY PANEL AREAS USED IN MATING AND DOCKING CONTROL



(Shaded Area Non-Primary)

FIGURE 3.2-8
PRIMARY PANEL AREAS USED IN DEXTROUS CONTROL



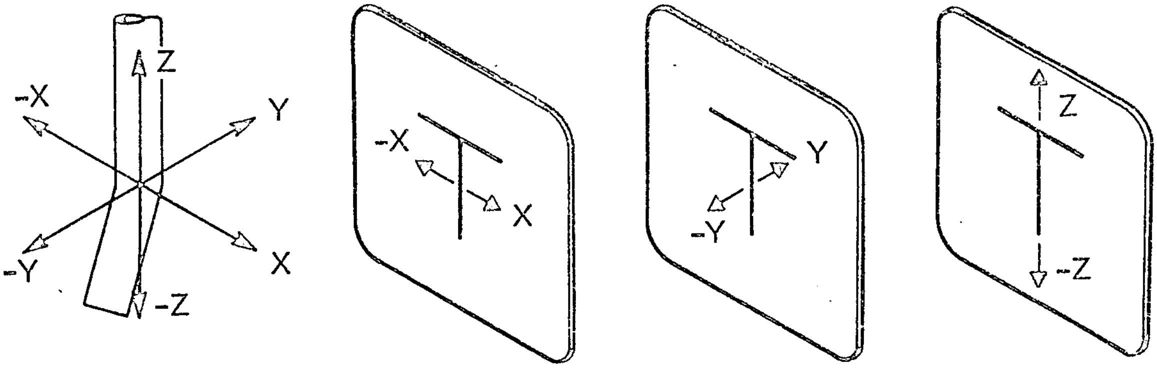
(Shaded Area Non-Primary)

FIGURE 3.2-9
PRIMARY PANEL AREAS USED IN EMERGENCY CONTROL

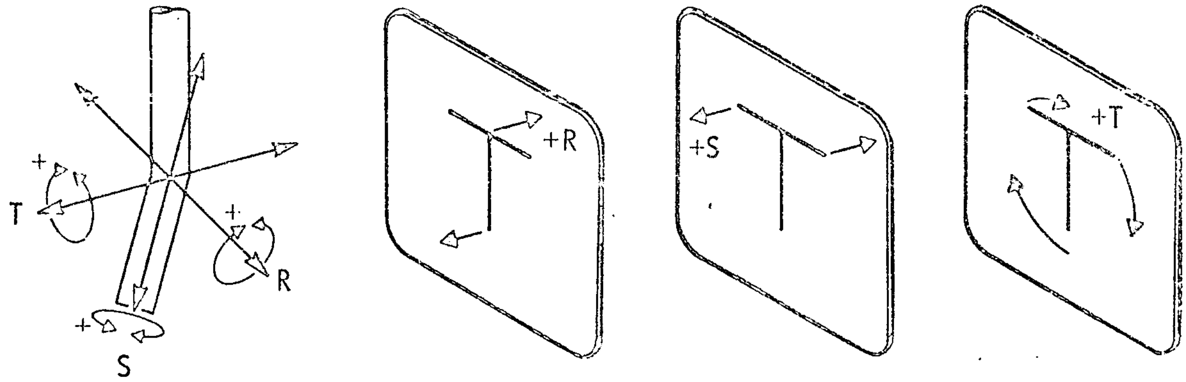
(end point rate control) and the connector must be plugged into the socket (orientor force reflecting position-position)] and for end point position-position force reflecting control (dexterous slave control). The use of a computer in the control system makes the above techniques practical since it is no longer necessary to have the complete conventional master-slave geometrically similar controller. The computer can perform the necessary coordinate transformations so that x, y z, θ, φ, γ movement of the controller end point and orientor cluster will result in corresponding movements of the boom (slave) end point and orientor cluster. Computerized end point rate control has been demonstrated at MIT.

The use of the computer also enables the operator to choose his frame of reference relative to the work scene. Simply by rotating the viewing camera the operator can present the work scene in a preferred orientation. The computer will then automatically move the boom or end effector relative to the way the operator views the work scene. This concept is illustrated schematically in Figure 3.2-10 where the "T" represents the work scene oriented to the operator as he chooses.

The feasibility of the boom scale model controller has been established in simulation studies conducted by MBA on this program. A model controller connected to NAT through a mini-computer is shown in the photograph in Figure 3.2-11. The model controlled 4 (2 shoulder, elbow and wrist flexure) of the 9 joints in the NAT arm. The 3 orientor joints were controlled separately in real time by the NAT grip controller. (The two arm roll motions were not used in these studies.) The computer was programmed to increase the time scale of the model motions by factors up to 20. The program was designed to smooth the model input motions, extrapolate ahead in time and if a very slow motion was encountered, speed that portion (still on an increased time scale) relative to the average trajectory time scale factor. Further detail on the experimental set up and simulation results are presented in Volume IV "Simulation Studies".



Control/Display Relationships in Translation



Control/Display Relations in Orientation

FIGURE 3.2-10
CONTROL/DISPLAY RELATIONS DURING
MATING AND BERTHING OPERATIONS

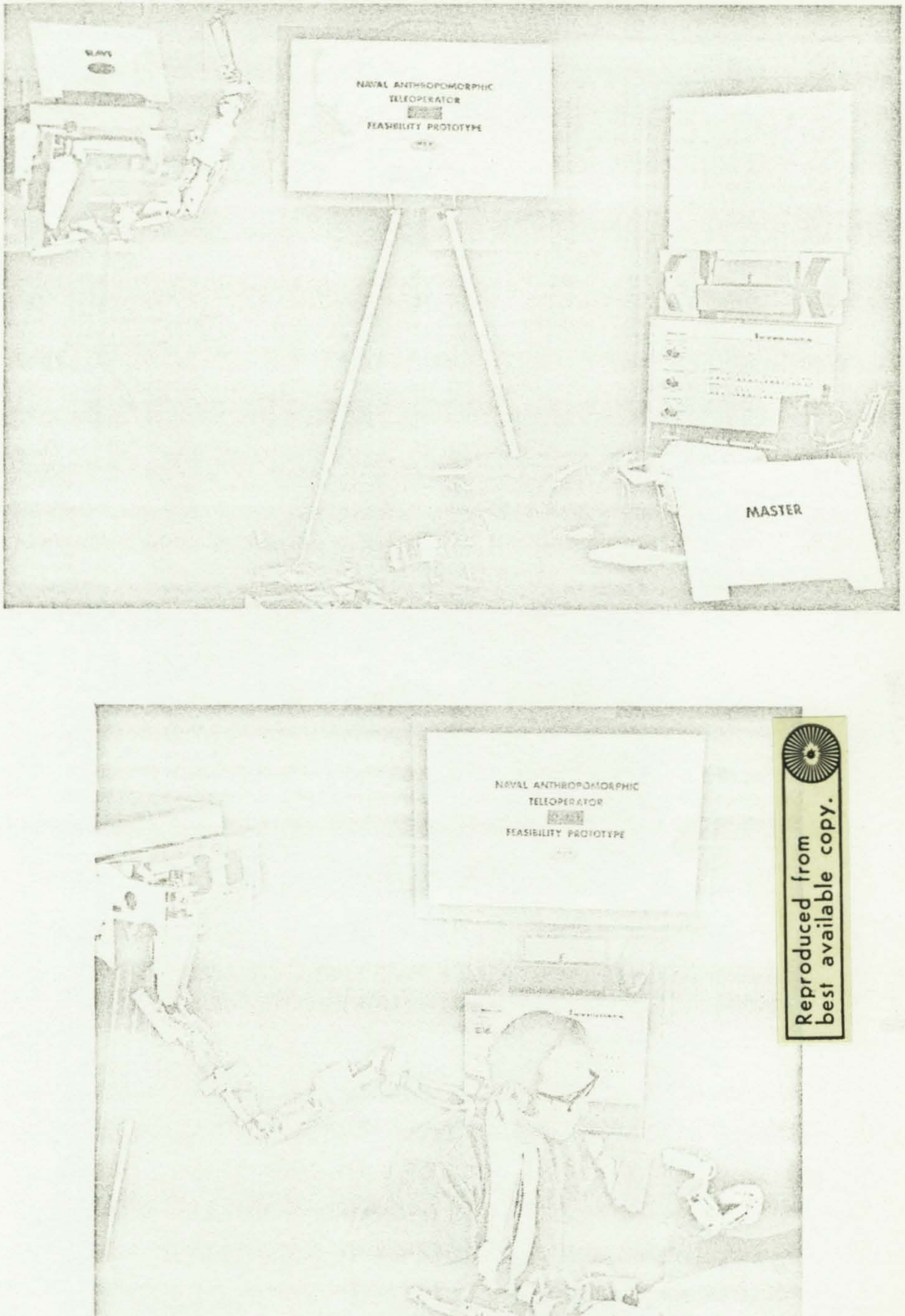


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FIGURE 3.2-11.
PHOTOGRAPHS OF SCALE MODEL COMPUTERIZED ARM CONTROLLER USED ON NAT. (Note The Adaptive Learning Demostrated In The Lower Photo.)

3.3 Visual System

Details of the visual system are presented in Section 6.5 "Visual System Analysis and Design". Key features of the system are described below.

3.3.1 Overall System

The overall visual system is illustrated schematically in Figure 3.3-1. It includes all of the features considered necessary to accomplish precise, dexterous tasks without direct viewing. The extent to which these features should be incorporated in an initial manipulator system will depend on the tasks to be accomplished, but ultimately it is expected that the complete system as selected will be required. The system includes the following:

- Stereo-Foveal Pointable Cameras on Manipulator & Dedicated Boom
- Simple Cameras at Berthing Ports and Cargo Bay
- Eye Acuity Matching (Foveal Technique)
- Stereoscopic with Split Field Counter-rotation
- Color Wheel
- Automatic: Focusing, Convergence, Brightness Control
- Image Tubes and Kinescopes with Fiber Optics Faceplates and Distortion Correction
- Fail Safe Feature (Automatic adjustments return to useable values if control fails)
- Parallax Panoramagram Stereo-Foveal Display
- Camera Pointing Control by Eye Tracking
- Incandescent Dual Beam 3 Lamp Illumination (all lamps not necessarily used simultaneously)
- Field Sharing Technique for Control of Brightness Gradients
- Optical Attachments (As required)
- Standby Stereotelescope (Back up)

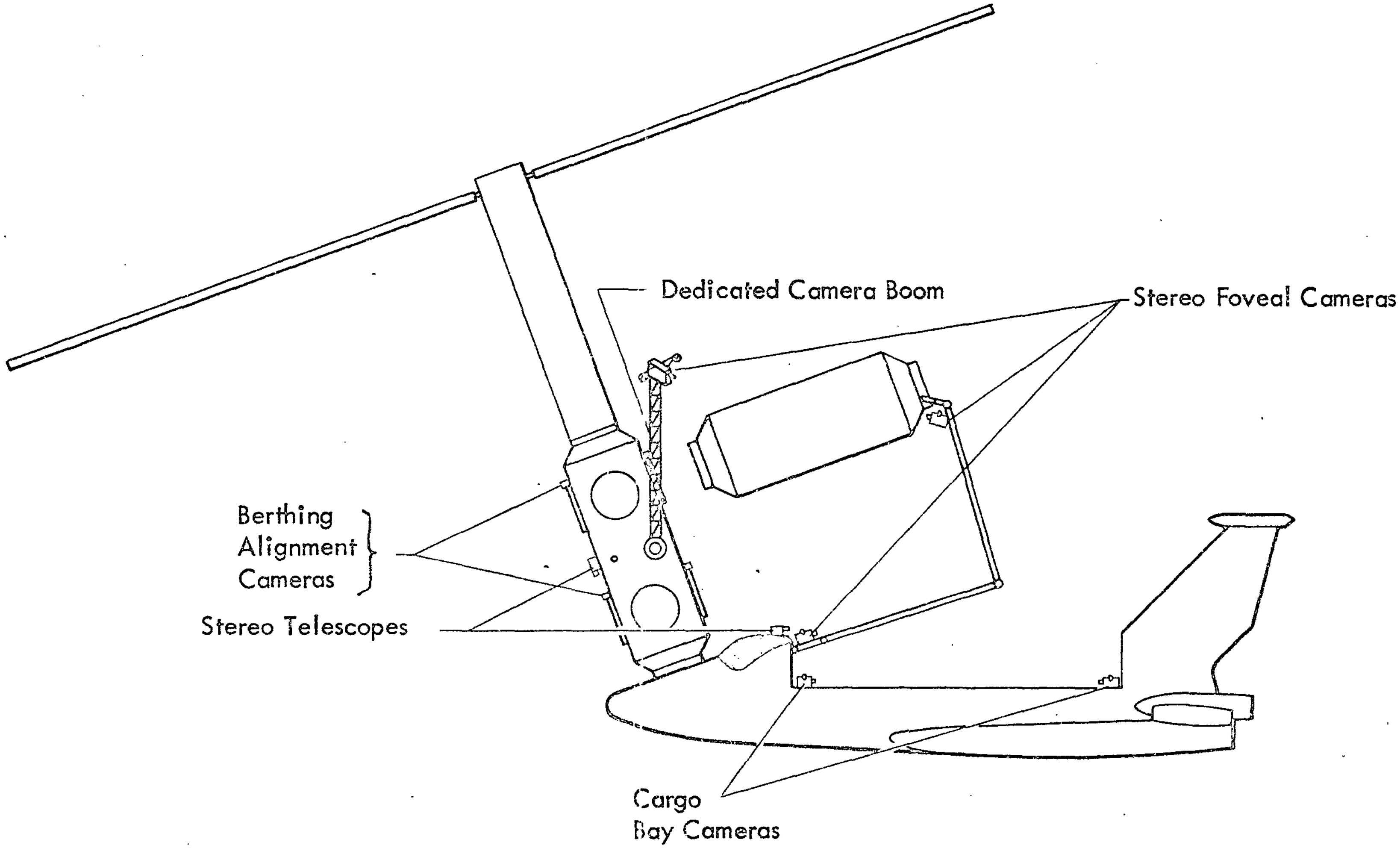

FIGURE 3.3-1
OVERALL VISUAL SYSTEM SCHEMATIC DIAGRAM

3.3.2 Dual Field Stereo-Foveal Concept

If precise tasks are to be accomplished at a distance with or without direct viewing, it is believed that stereoscopic viewing will be required to make the manipulator/end effectors fully effective. Furthermore high resolution will be required particularly for inspection and work with small/fine parts. The foveal concept when the work scene resolution is displayed analogous to the eye angular acuity distribution is an attractive technique which has been selected in order to provide resolution where the eye can use it (the center foveal region) but at the same time conserve on video bandwith (low resolution in the peripheral area). A sample two field foveal/peripheral display is shown in Figure 3.3-2. By this technique the operator is presented with high resolution at the immediate work scene when he needs it, yet he still has an overall wide field-of-view to maintain a perspective of the geometrical relationships of the work relative to its surroundings.

By presenting the foveal region in stereo the operator can also get the depth perception required for precise work. The feasibility of this technique was demonstrated by simulation studies performed in this study. (See Volume IV "Simulation Studies".) The camera and display arrangements for a practical stereo-foveal system are described below.

The dual field concept also offers an interesting approach for dealing with high contrast illumination situations. The available camera image tubes have the dynamic range to accommodate and very low illumination levels to direct exposure to sunlight; however, they cannot simultaneously accommodate such a range. The dual field concept makes it possible to use the foveal field at one level of illumination and the peripheral field at another such as illustrated in Figure 3.3-3. The selected sunlight illumination approach is based on this concept.

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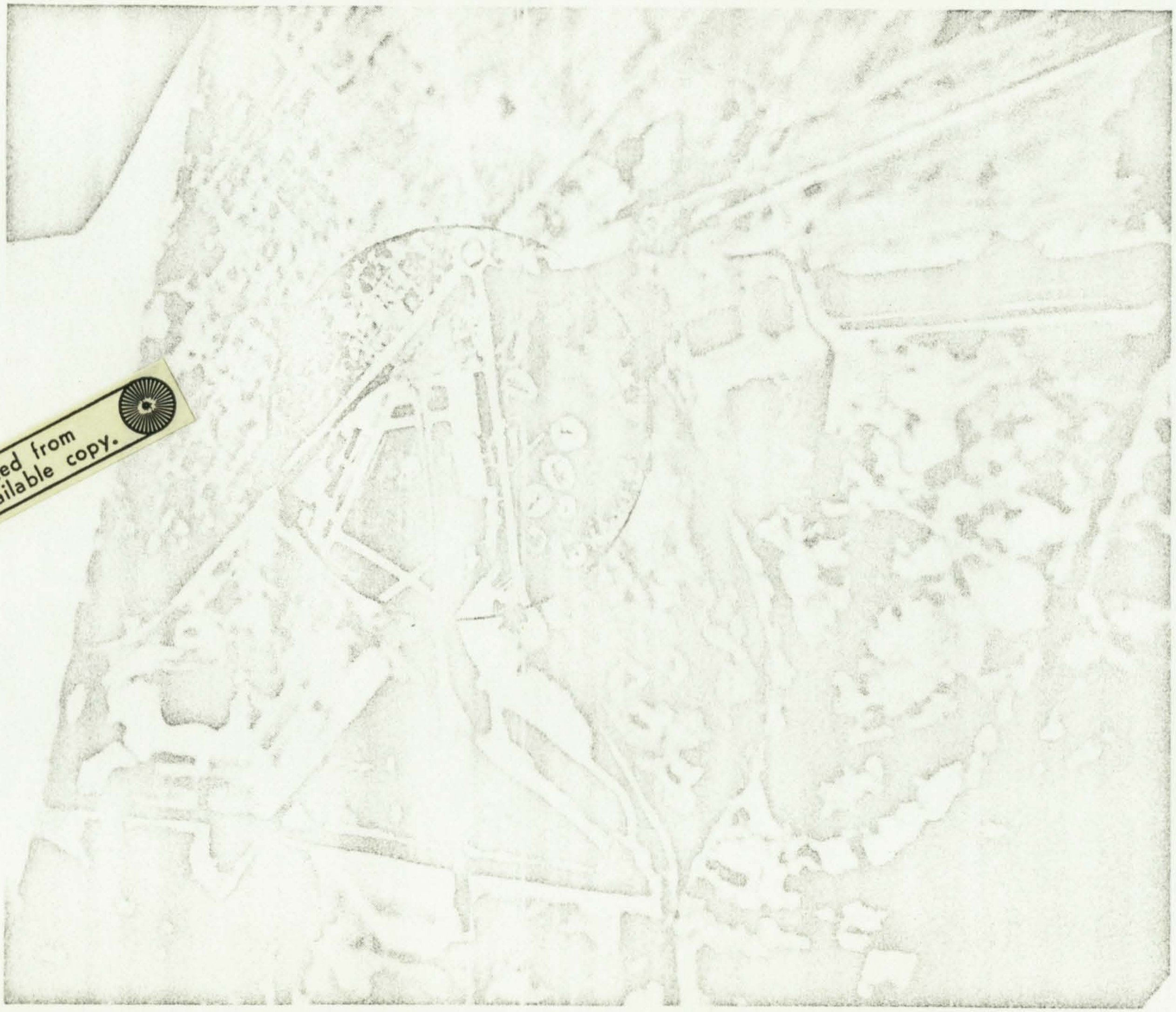
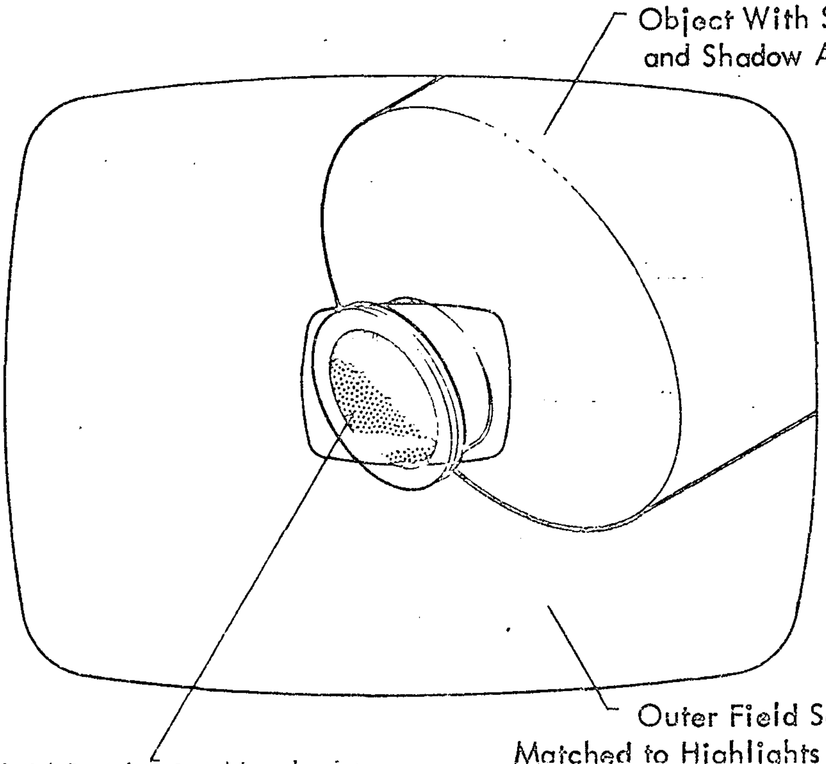


FIGURE 3.3-2
FOVEAL AND PERIPHERAL FIELDS AS SEEN THROUGH CDC HAT SYSTEM



Object With Sun Lights and Shadow Areas

Central Field Sensitivity Matched to Shadow, Highlight Washed Out

Outer Field Sensitivity Matched to Highlights - Shadow Details Not Sensed

FIGURE 3.3-3
USE OF FOVEAL CAMERA DUAL FIELD ZOOM AND MOBILITY FOR SIMULTANEOUS VIEWING OF SHADOWED AND HIGHLIGHTED AREAS IN SUNLIGHT

3.3.3 Dual Field Stereo-Foveal Cameras

The general concept is to blank out the central field of the wide angle camera and use a stereoscopic narrow field camera to superimpose a view in its place. The general camera arrangement is illustrated in Figure 3.3-4. Only two (2) cameras in conjunction with a system of mirrors and prisms are used. By having the two cameras attached to each other their field registration is held constant. The beam splitter is used to bring the peripheral and foveal fields into concentricity. The stereo attachment is used to split the field and provide the stereo base (separation) for the lower "stereo" camera. In this manner no stereoscopic disparity is introduced by having different cameras with their unavoidable variations (tolerances) in image tubes, circuits, etc. Disparities are further reduced by counter rotating the images so that they register on the image tube as shown schematically in Figure 3.3-5. Thus corresponding image elements are registered in point symmetric positions on the image tube.

3.3.4 Dual Field Stereo Panel Display

The manner in which the dual field stereo-foveal image is displayed on a panel is illustrated in Figure 3.3-6. The video output from the two cameras are fed to their respective display tubes and a system of lens, mirrors and beam splitters is used to project a real superimposed two field concentric image on the liquid crystal backlighted screen. A liquid crystal screen (rather than ground glass) is used to obtain high resolution and controlled scattering angle. The stereo field is divided electronically into vertically strips of left and right sub-fields. A vertical lenticular face plate (lens system) is placed over the real image screen where the image is registered such that a pair of left and right sub-fields are covered by each sub lens of the face plate. The sub lens separate the left and right sub-fields such that, with the operator positioned in the viewing area, the left eye sees only the left fields and the right eye the right fields resulting in stereoscopic perception by the operator. This system will permit the operator to move left and right

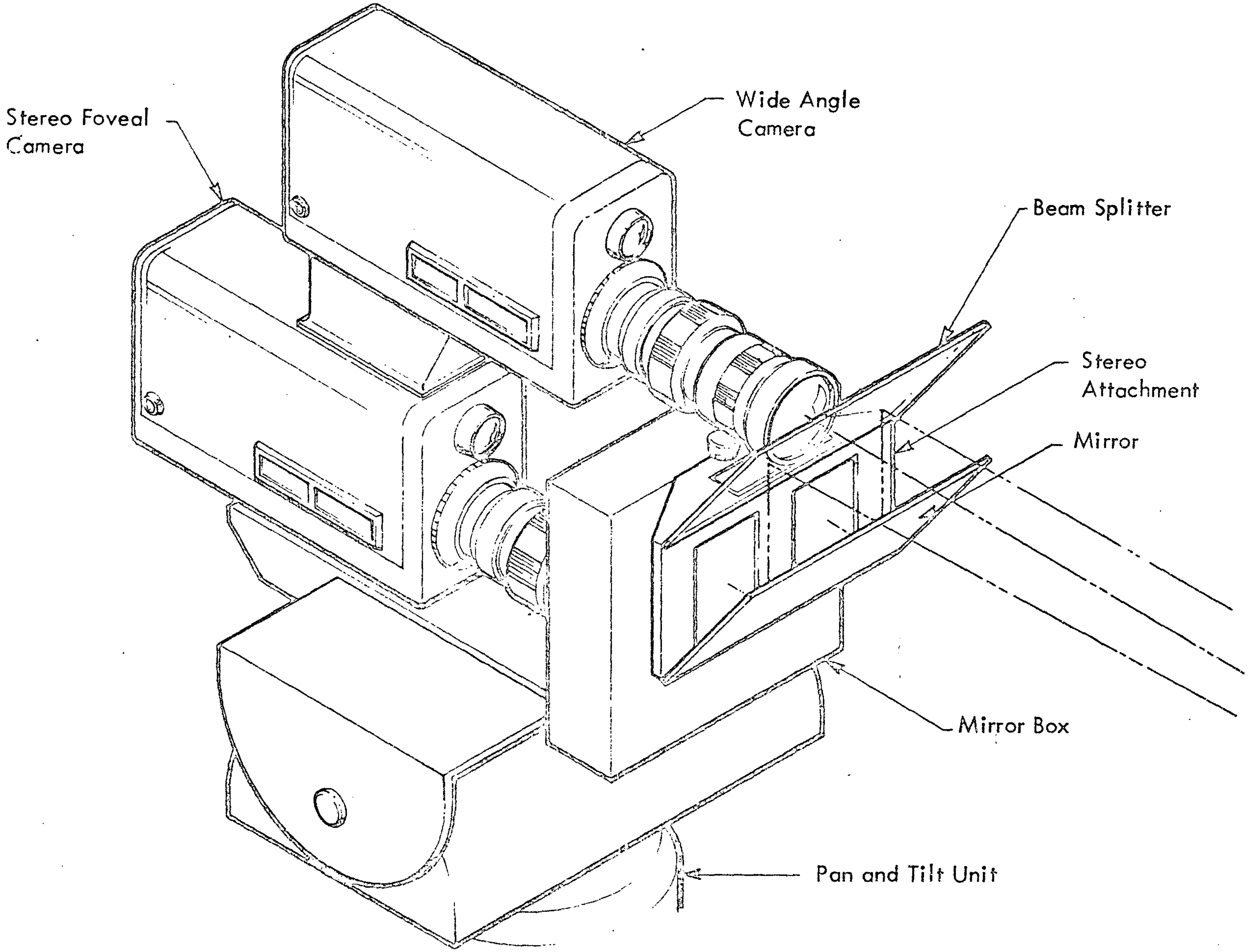


FIGURE 3.3-4
DUAL FIELD STEREO FOVEAL CAMERA SYSTEM ASSEMBLY

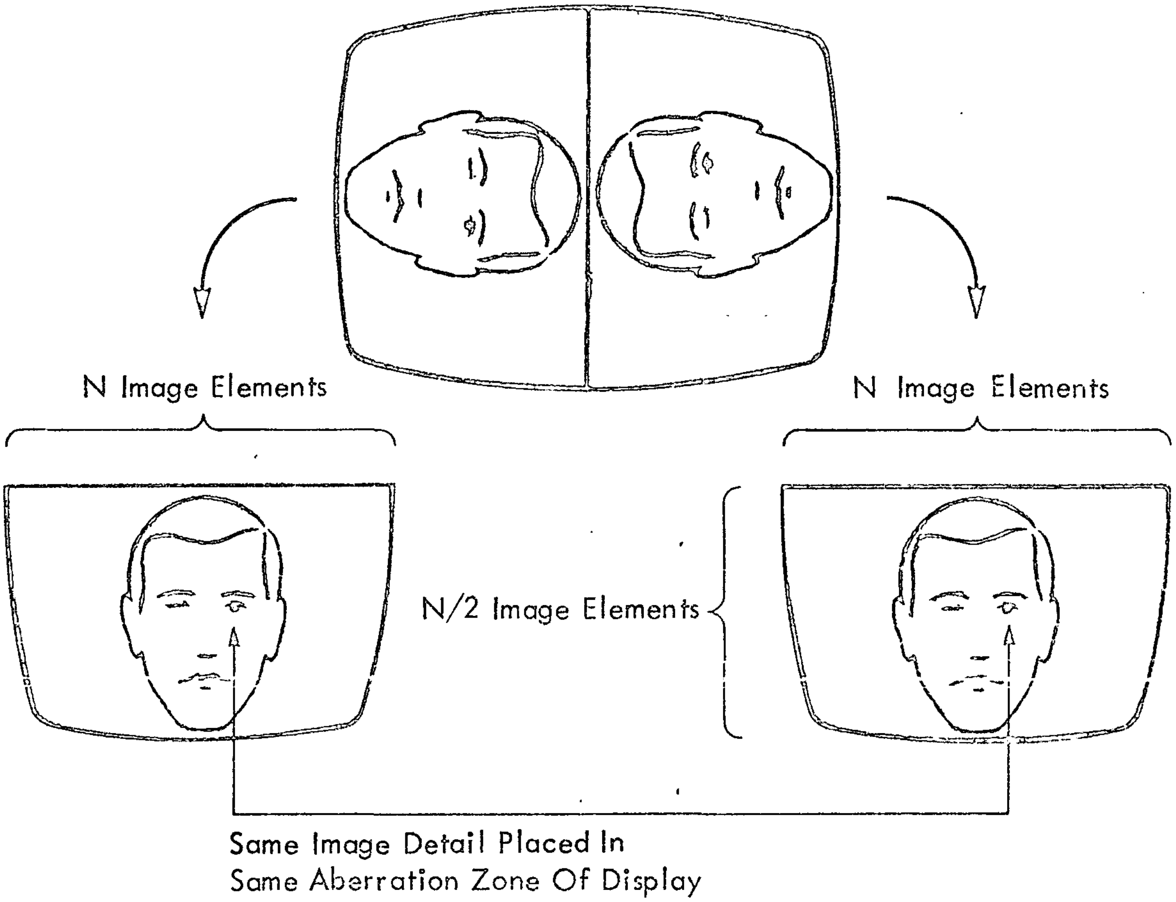


FIGURE 3.3-5
SPLIT FIELD STEREOSCOPIC VIDEO DISPLAY 90° IMAGE COUNTERROTATION WITHOUT NON-STEREOSCOPIC IMAGE DISPARITIES AND HORIZONTAL RESOLUTION HIGHER THAN VERTICAL RESOLUTION FOR ECONOMY OF BANDWIDTH

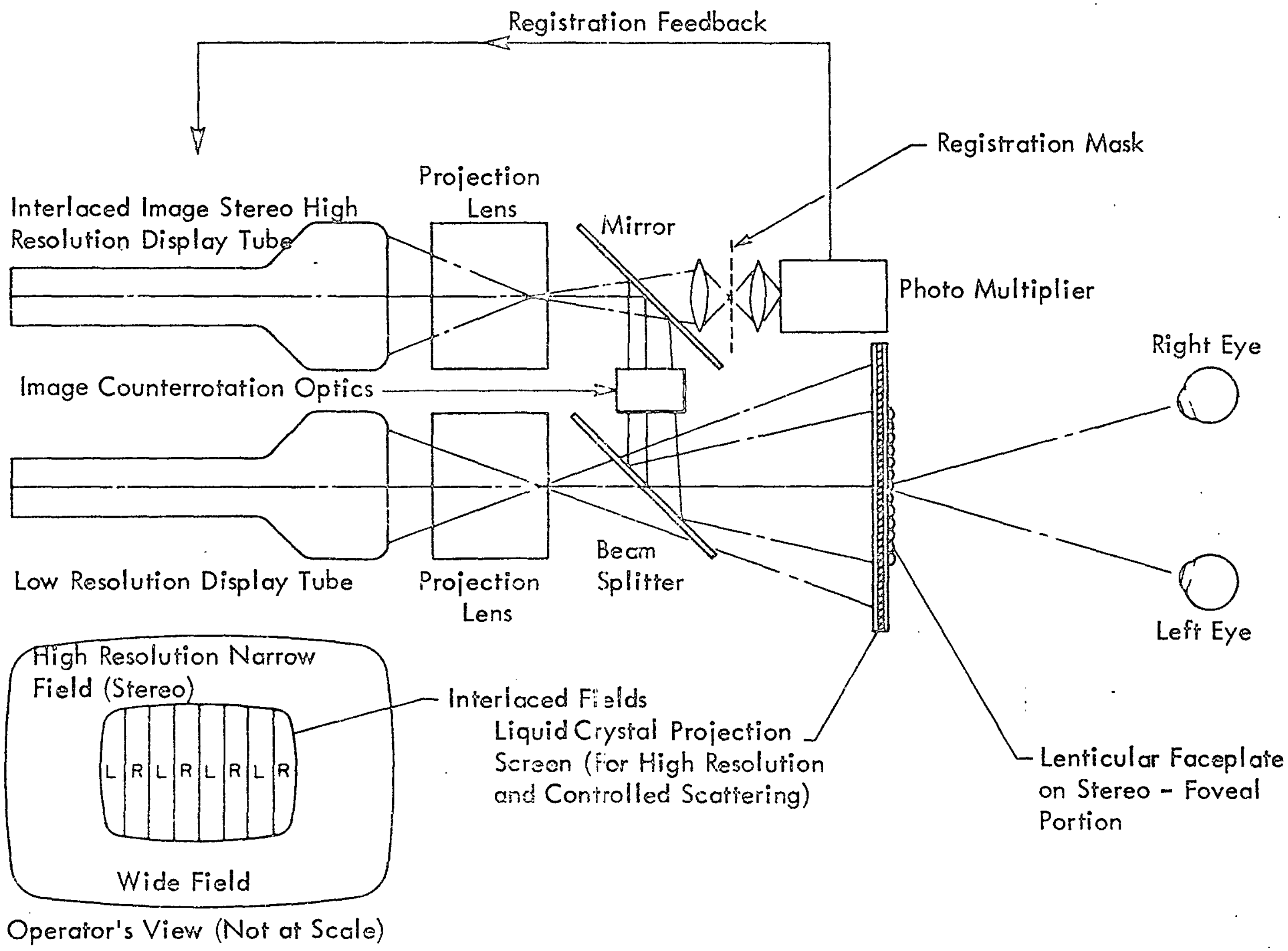


FIGURE 3.3-6
REAL IMAGE DISPLAY WITH PARALLAX STEREOGRAM AND INTERLACED LEFT-RIGHT STEREO FIELDS.

about ± 15° and back and forth about ± 20% of his distance from the panel without degrading the perceived stereo image. Commercially available stereo photographs based on this principle and providing very good stereo perception are readily available (for example "Lentograph^{R}" by Victor Anderson 3D Studies Inc, Port Chester, New York).

3.4 Boom Control System

The boom control system, which includes the computer and its software, as well as the electronics, is discussed in detail in Section 6.6, "Boom Control System Analysis and Design". Salient features of the system are described below. It should be noted that the dedicated viewing boom would be controlled in the same manner as the main boom.

3.4.1 Overall System

The integrated computer control system is illustrated in Figure 3.4-1. The emergency control system which is used if the computer fails is illustrated in Figure 3.2-5. The computer control system is not used to control the TV displays since the operator directly selects and controls the cameras he wants, their orientation, etc.

The operator displays shown in Figure 3.4-1 consist only of computer processed information such as joint positions, status etc. The computer hardware requirements are summarized in Table 3.4-1. Investigation of the space station computer requirements indicates that there should be sufficient capacity to handle the manipulator system requirements. On the shuttle it appears that additional memory capacity, or perhaps even a separate dedicated computer, will be required.

3.4.2 Computer Software

The boom configuration is defined by the co-ordinate system shown in Figure 3.4-2. Co-ordinate x, y, and z, define the end point as it has been used in this report. Note that it is the point at which the wrist assembly attaches but does not include the moveing elements of the wrist. For this case, if the intermediate shoulder joint is fixed (i.e., used only as an indexing joint) the end point is defined by three boom angular co-ordinates (α, φ, β). A unique closed form analytical transformation can then be written for x_1, y_1, and z_1 in terms of α, φ, and β. Thus, when the operator commands values of $\dot{x}_1$, $\dot{y}_1$, and $\dot{z}_1$, the computer algorithm can solve directly for $\dot{\alpha}$, $\dot{\varphi}$, and $\dot{\beta}$ to provide the command motion. If, however, the "indexing" joint is made active (to clear obstacles, for example) or if one or more of the wrist joints are included in the "end point", there are then more unknowns (boom joint co-ordinates) than there are

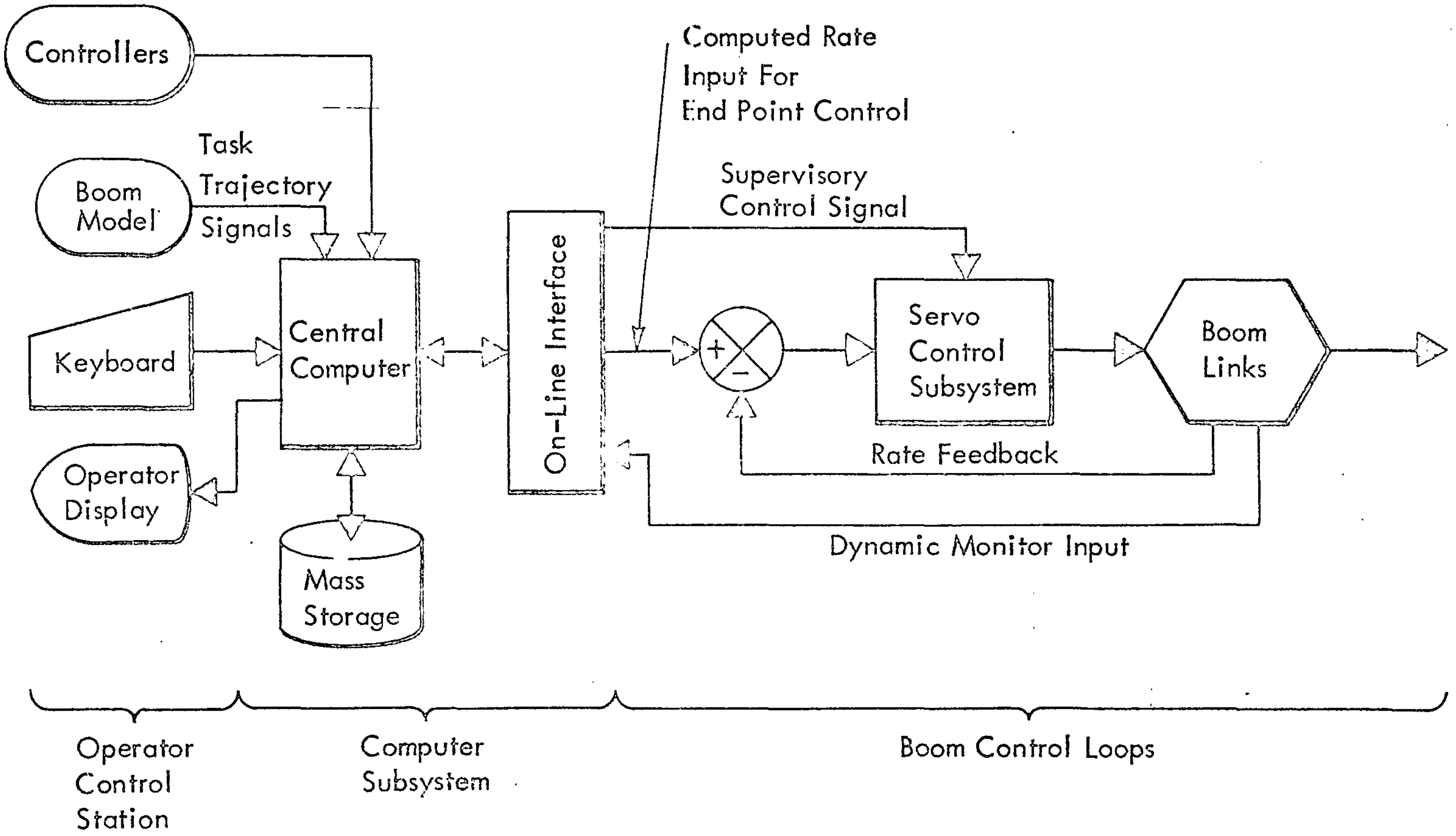


FIGURE 3.4-1
THE INTERGRATED COMPUTER CONTROL SYSTEM

PROGRAM FUNCTION	OPERATIONAL MEMORY	OFF-LINE STORAGE	REQUIRED RESPONSE TIME
Environmental Model Storage	10 k	150 k	Not Applicable
Supervisory Control Program	8 k	60 k	1 sec.
End Point Control Program	8 k	0	50 m sec.
Dynamic Monitor	2 k	0	100 m sec.

TABLE 3.4-1
COMPUTER HARDWARE REQUIREMENTS
FOR THE BOOM CONTROL SYSTEM

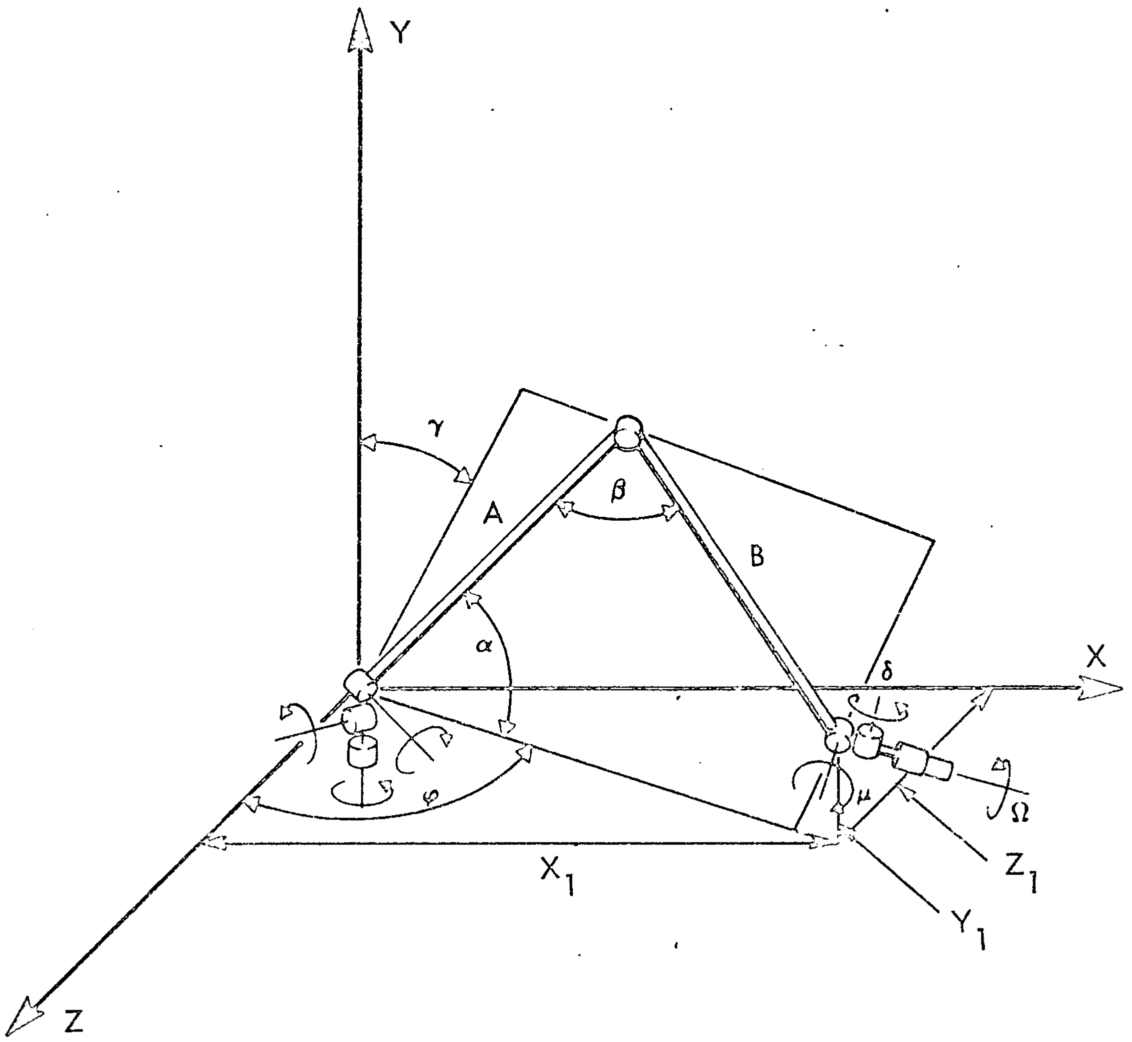


FIGURE 3.4-2
BOOM COORDINATE SYSTEM

equations (functions for x, y and z). In other words, there are redundant boom configurations that can provide the same "end point" location. The latter situation is a more general case. A block diagram of the program selected to solve the case where the shoulder index joint is active, is shown in Figure 3.4-3. In essence, the algorithm computes 81 iterations and uses a minimizing criterion to select the next preferred boom joint configuration (it actually outputs the angular rates to reach that configuration). Although it is not shown in Figure 3.4-3, the computer must also confirm that the boom will not strike obstacles when it moves as described below.

In supervisory control, the operator commands a specific task already stored in the computer memory or newly programmed into the computer. He then simply monitors the task as the computer takes over control and implements the task. Figure 3.4-4 shows a block diagram of the supervisory control program. In addition to selecting or programming a specific task, the operator must input any new geometric data on the shuttle and/or station configuration so that the computer can generate an updated environmental model. The environmentalmodel is used to determine trajectory paths and avoid collisions.

The scale model trajectory following control program is illustrated in Figure 3.4-5. The operator sets up the model boom and model shuttle/space station in their proper relationship. As he then moves the model in a desired trajectory about the shuttle/space station, the model joint histograms are fed into the computer. The histograms are smoothed and expanded by a preselected time factor. When ready and on command, the computer then drives the boom on the desired trajectory on a time scale compatible with the boom capability and requirements. The model controller would only be used for end point trajectory control or approximate "wrist end point trajectory" control. By use of the master controllers the operator can control the wrist in real time while the computer controls the end point in expanded time. The control system for this mode is illustrated in Figure 3.4-6.

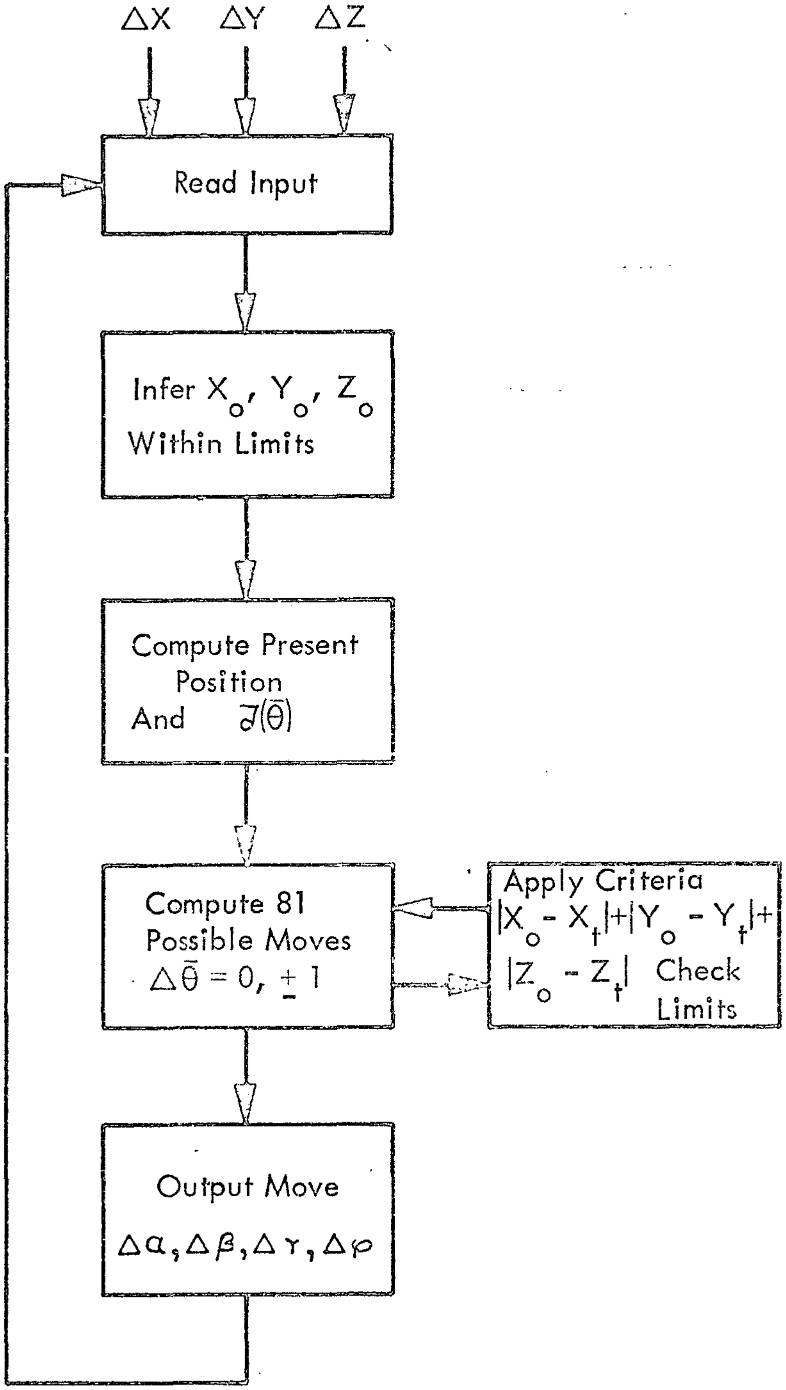


FIGURE 3.4-3
END POINT CONTROL PROGRAM

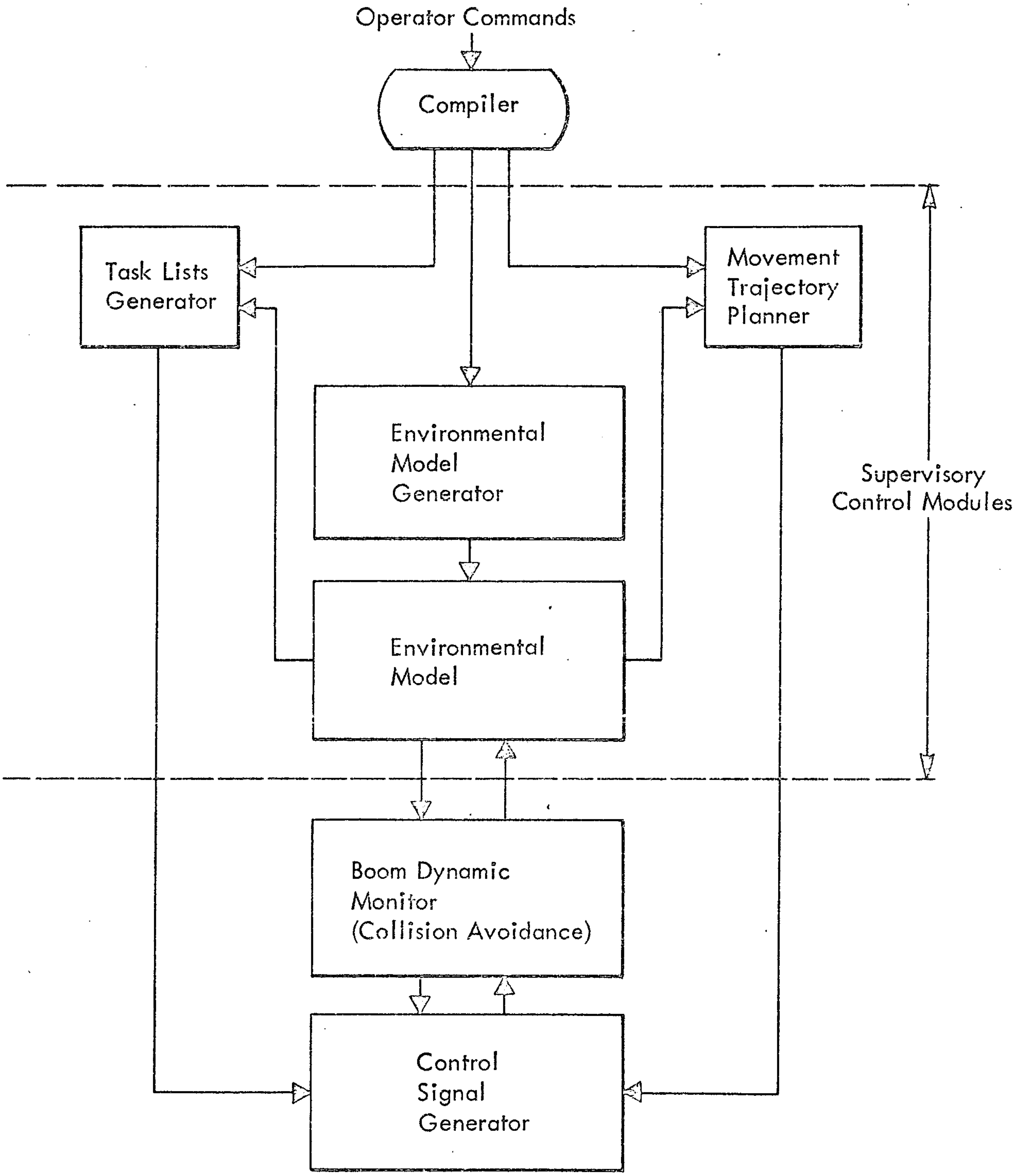


FIGURE 3.4-4
SUPERVISORY CONTROL PROGRAM

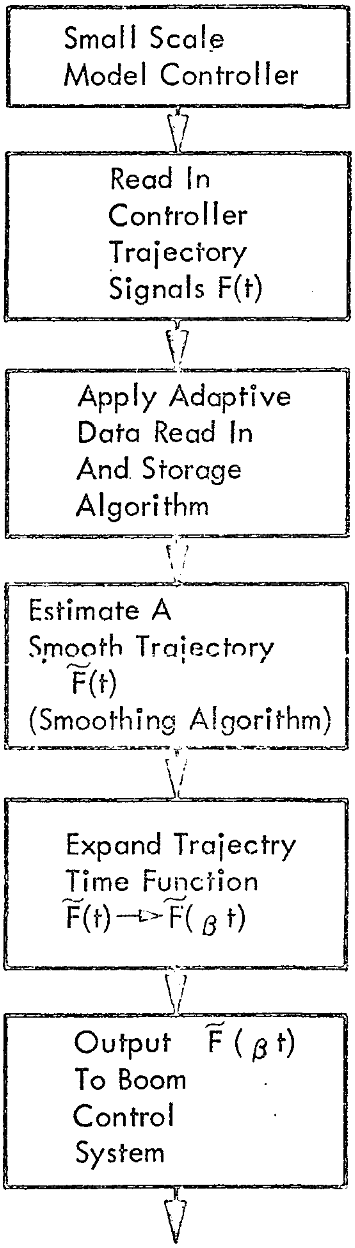


FIGURE 3.4-5
TRAJECTORY FOLLOWING CONTROL PROGRAM

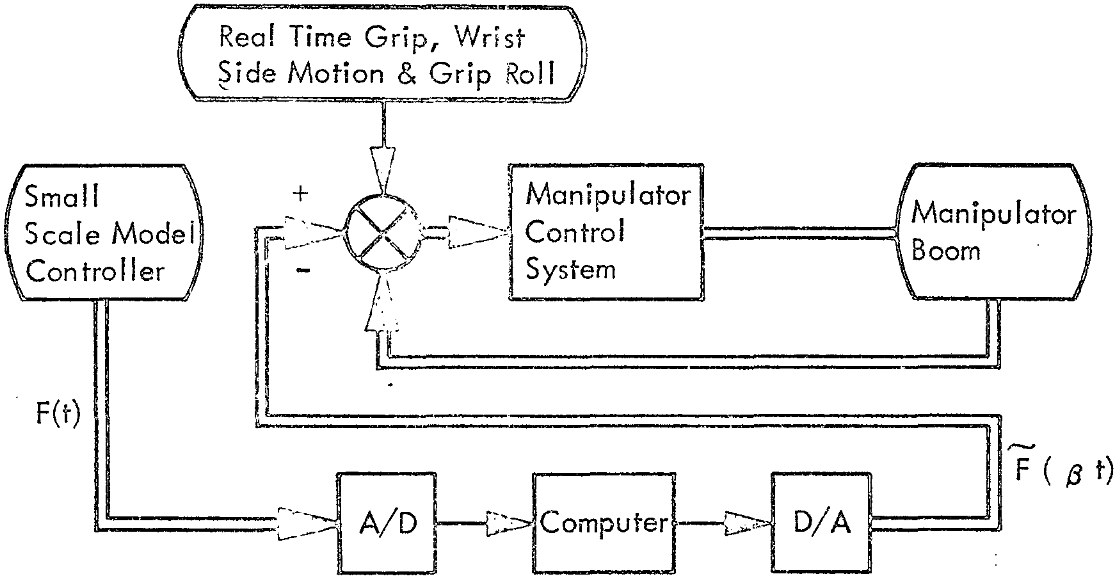


FIGURE 3.4-6
TRAJECTORY FOLLOWING CONTROL SYSTEM

3.4.3 Electronic Control System

A schematic functional block diagram of the boom control system including telecommunications is shown in Figure 3.4-7. The manual commands and display inputs fed directly between the interface and control station include the controls and displays for emergency operations and camera positioning and adjustment. The signal density for the various commands and monitor functions are summarized in Table 3.4-4.

A typical actuator control system is shown in more detail in Figure 3.4-8. The shaft encoder reads the joint position down stream of the slip clutch so that registration is not lost if the joint is forced to slip. The tachometer is attached directly to the motor to provide a direct rate measurement. Joint slippage is indicated (within the tolerance of the tachometer and integrating circuits) when the position determined by rate integration differs from the direct position measurement.

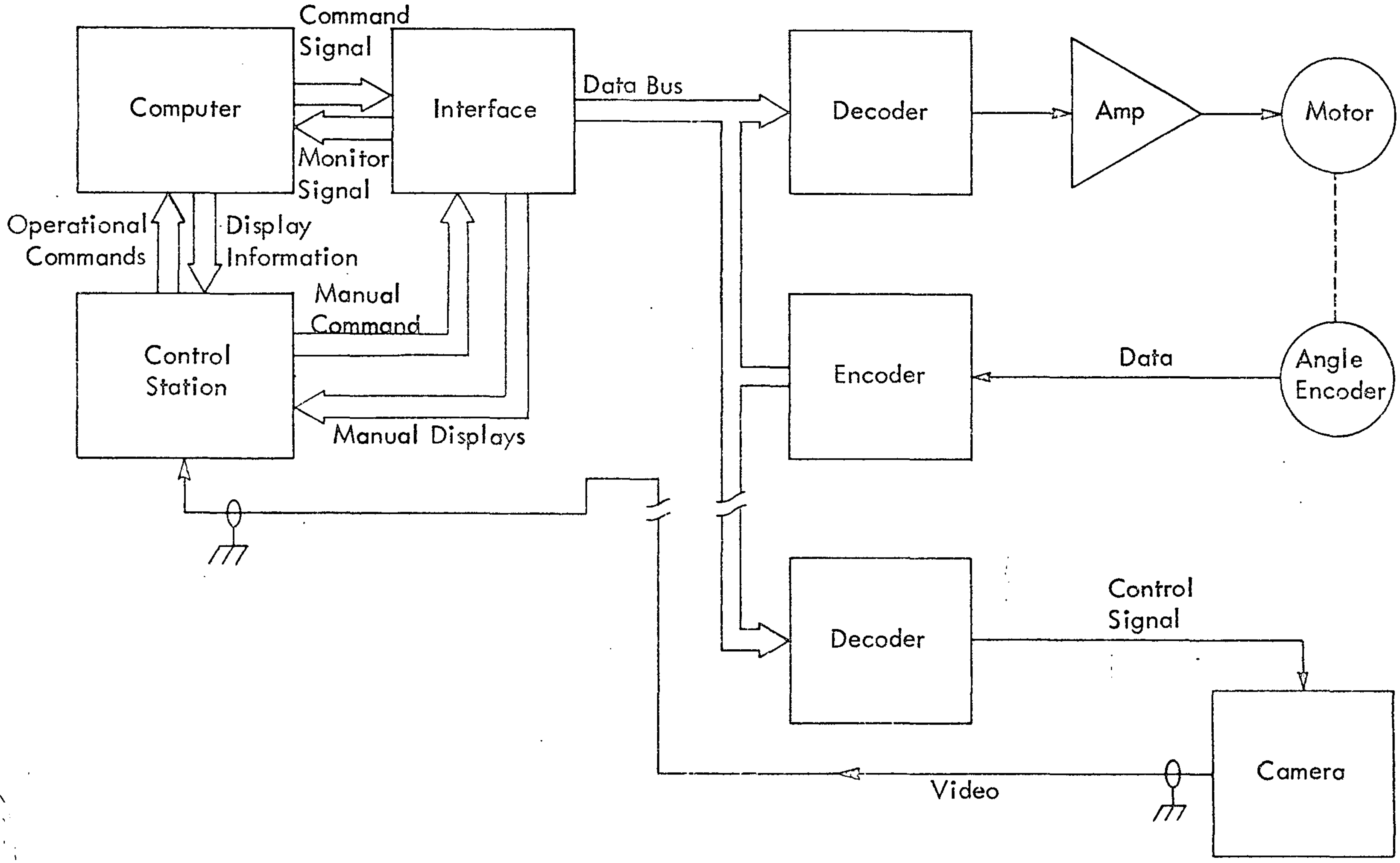


FIGURE 3.4-7
BOOM CONTROL AND TELECOMMUNICATION SYSTEM

Function	Number			Rate / Sec	Bits			Words / Sec
	Boom	Dextrous T/O	Viewing Boom		Address	Command	Monitor	
Monitor Arm Force	7	14	6	100	8	0	10	2700
Command Arm Force	7	14	6	100	8	10	0	2700
Monitor Arm Position	7	14	6	100	8	0	10	2700
Monitor T/O Housekeeping	30	60	20	1	8	0	10	110
Command TV Control	4	4*	2	10	8	10	0	100
Monitor TV Housekeeping	20	20	10	10	8	0	10	500

Notes:

*Commands Are Bang-Bang Rate On Off Control
2 PCM Command Words = 20 Bits = 10 Commands
On/Off Focus, Zoom, Light Iris, Adjust B/W
Adjust Color (5) Adjust Stereo/Foveal (5)

TABLE 3.4-4
COMMAND MONITOR SIGNAL DENSITY SUMMARY

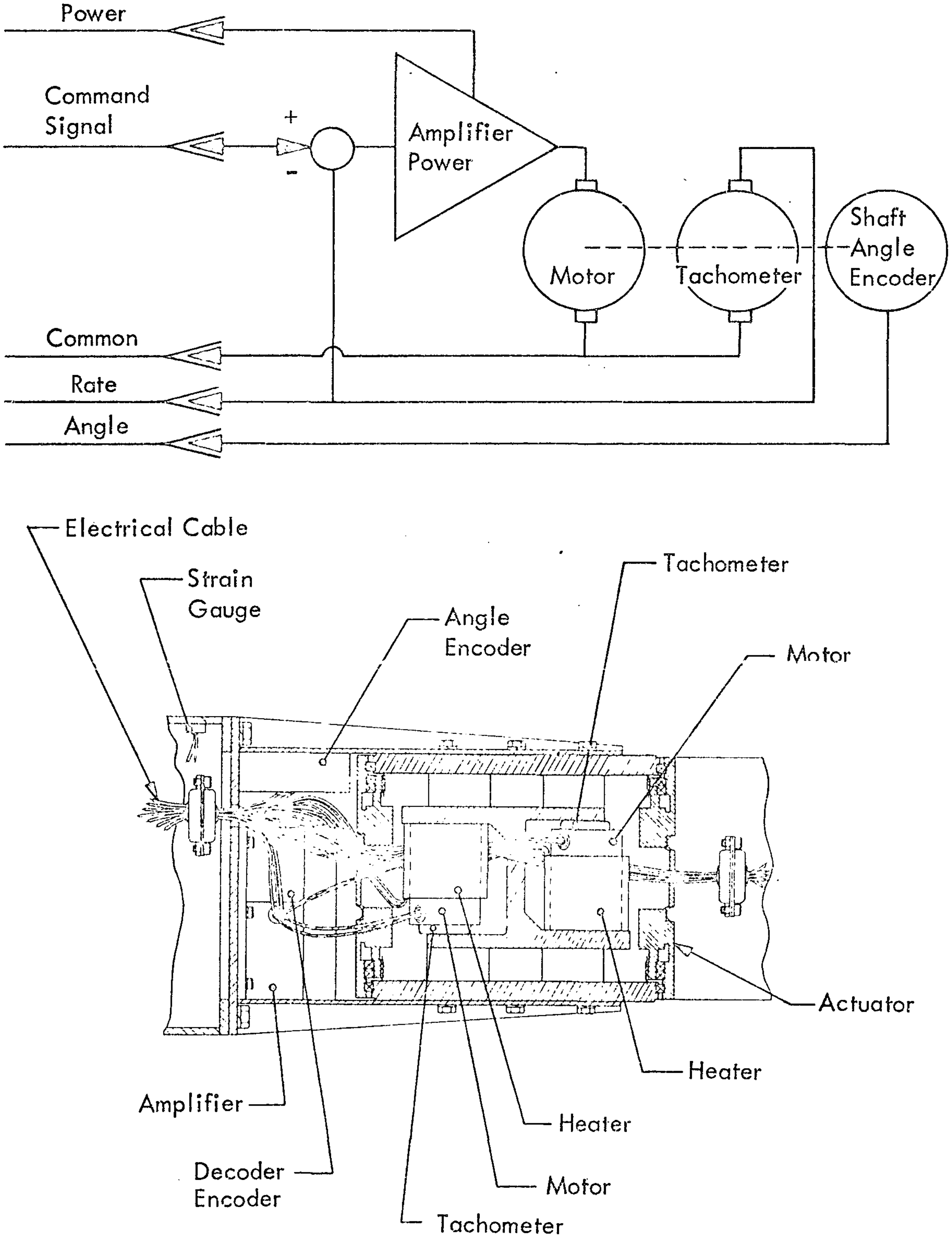


FIGURE 3.4-8
ACTUATOR CONTROL SYSTEM

3.5 Utility

An approach for servicing the Large Space Telescope, a brief summary of the possible manipulator requirements for the first 10 shuttle missions and scale model illustrations of space station assembly and maintenance are presented below. Further considerations on the manipulator system utility including station propulsion package replacement and ways of improving direct viewing from the shuttle are presented in Section 6.10 "System Utility Analysis".

3.5.1 Servicing the LST

Possible manipulator root point locations on the shuttle are illustrated in Figure 3.5-1. 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 3.5-2 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.

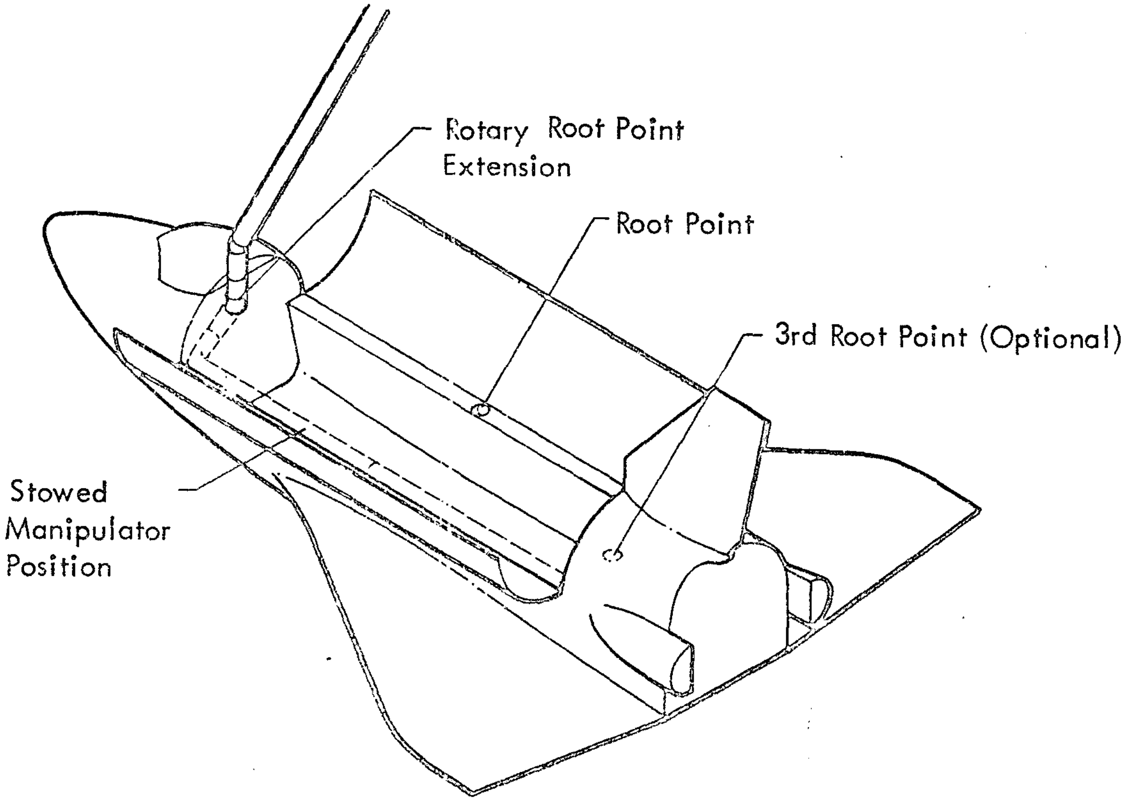


FIGURE 3.5-1
SHUTTLE SWING ARM AND FIXED ROOT POINT LOCATIONS (2)

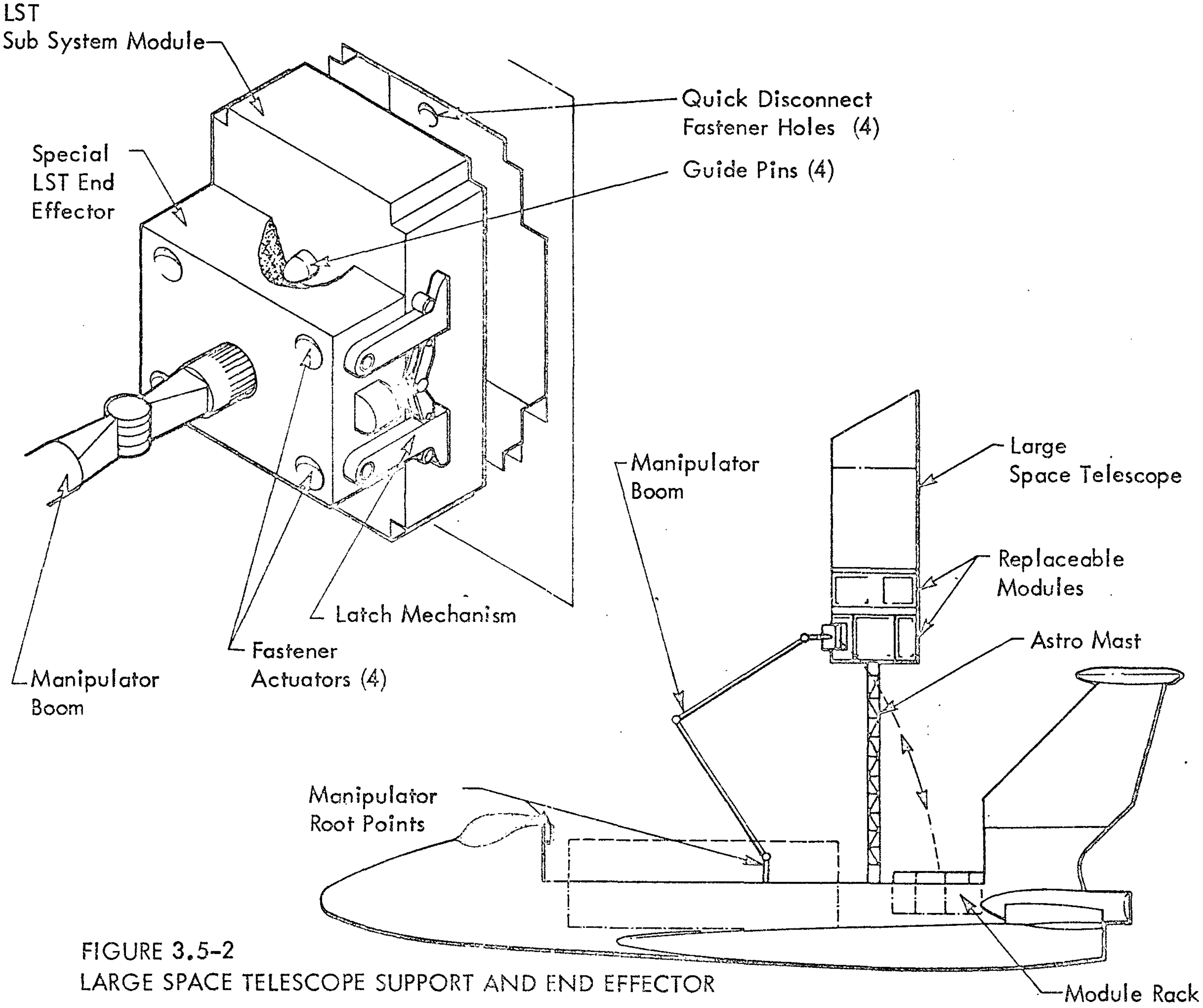


FIGURE 3.5-2
LARGE SPACE TELESCOPE SUPPORT AND END EFFECTOR

3.5.2 The First Shuttle Mission

Table 3.5-1 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 3.5-2. 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.

3.5.3 Space Station Assembly and Maintenance

Figure 3.5-3 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 3.5-4, -5, -6, -7 and -8 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 3.5-1
FIRST TEN SHUTTLE MISSIONS -- MANIPULATOR REQUIREMENTS SUMMARY

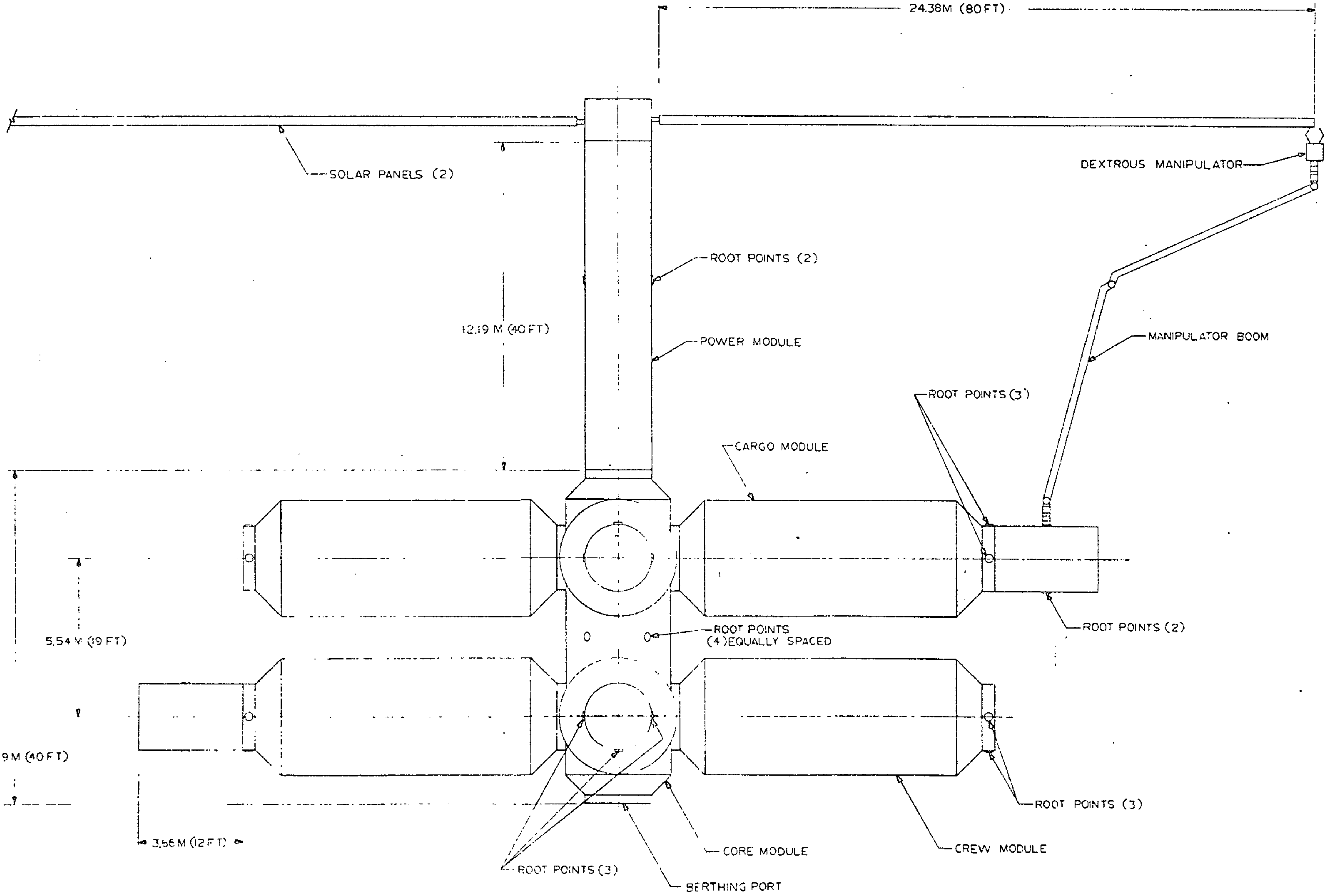


FIGURE 3.5-3
ASSEMBLED SPACE STATION SHOWING ROOT POINTS AND MANIPULATOR

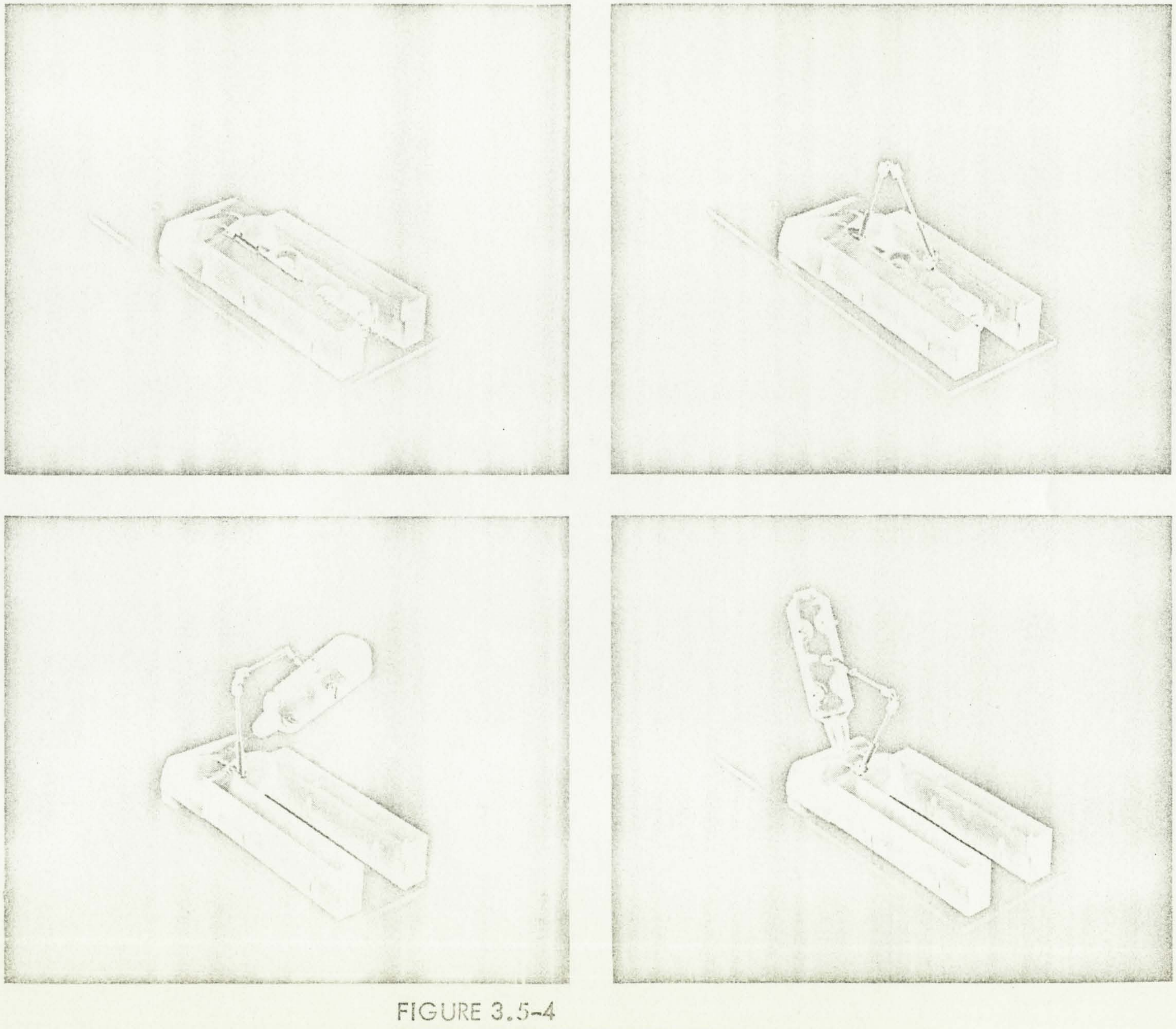


FIGURE 3.5-4
CORE MODULE DEPLOYMENT

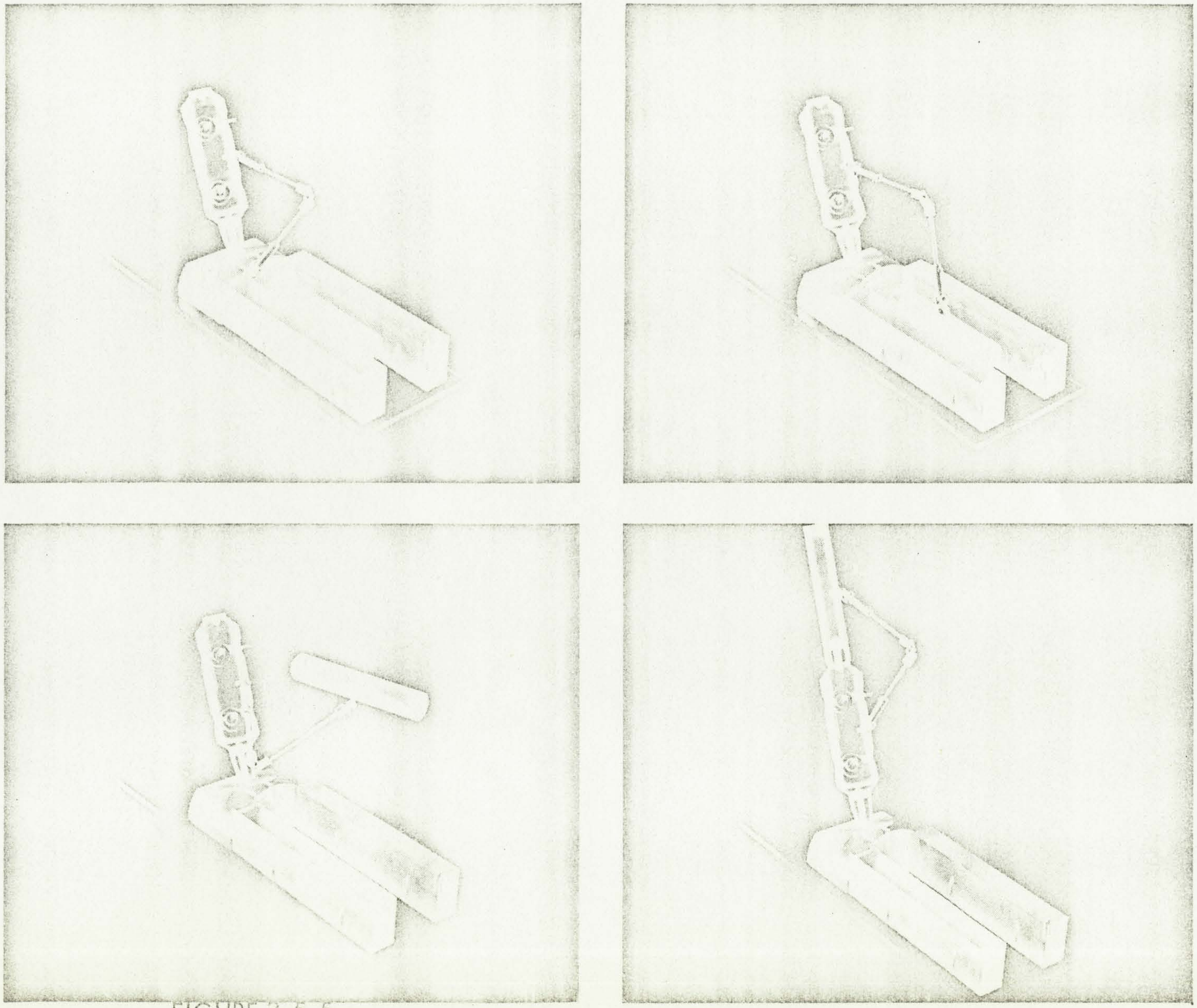


FIGURE 3.5-5
SOLAR PANEL/POWER AND CORE MODULE ASSEMBLY

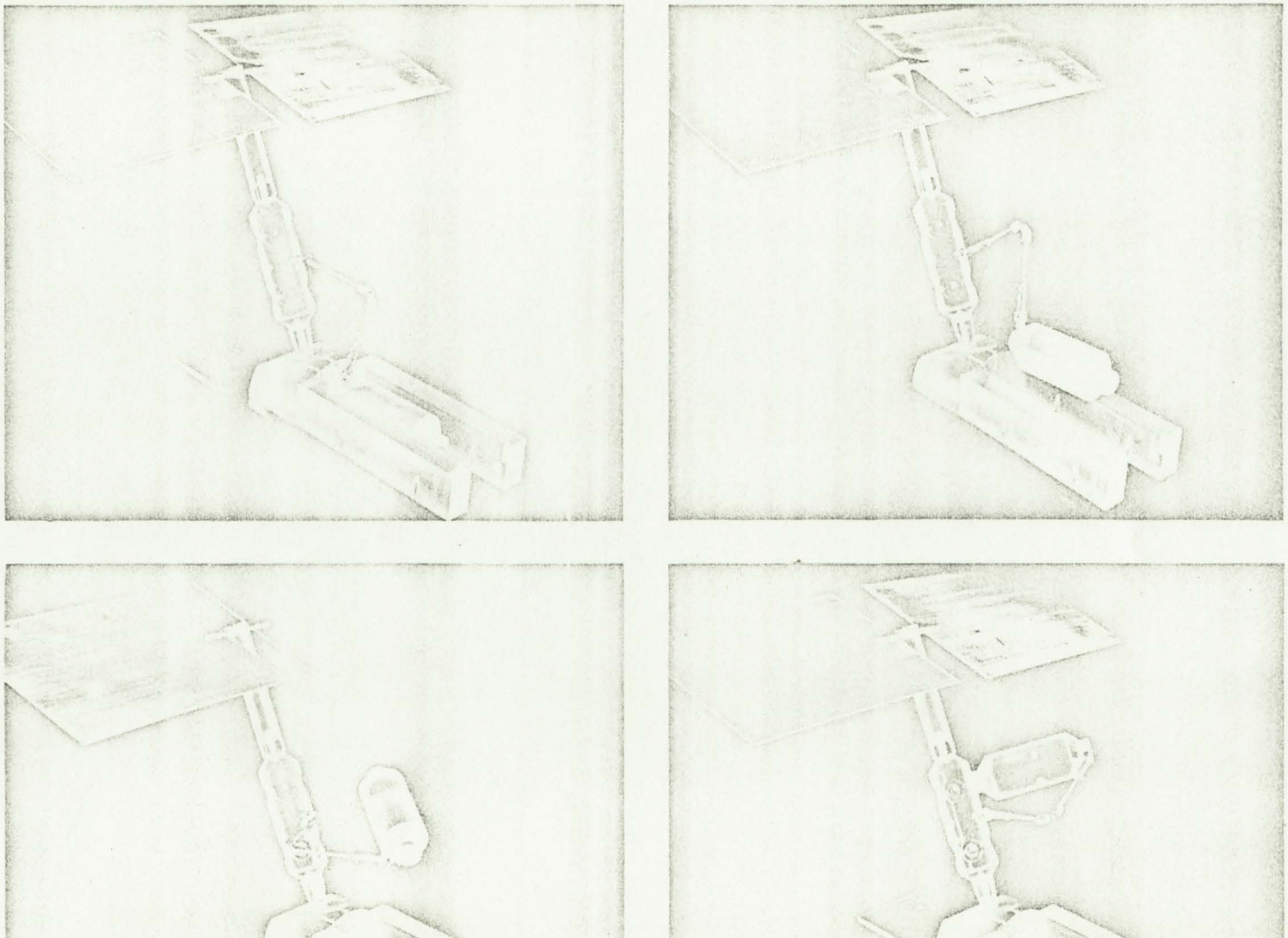


FIGURE 3.5-6
CONTROL/CREW MODULE TO CORE ASSEMBLY

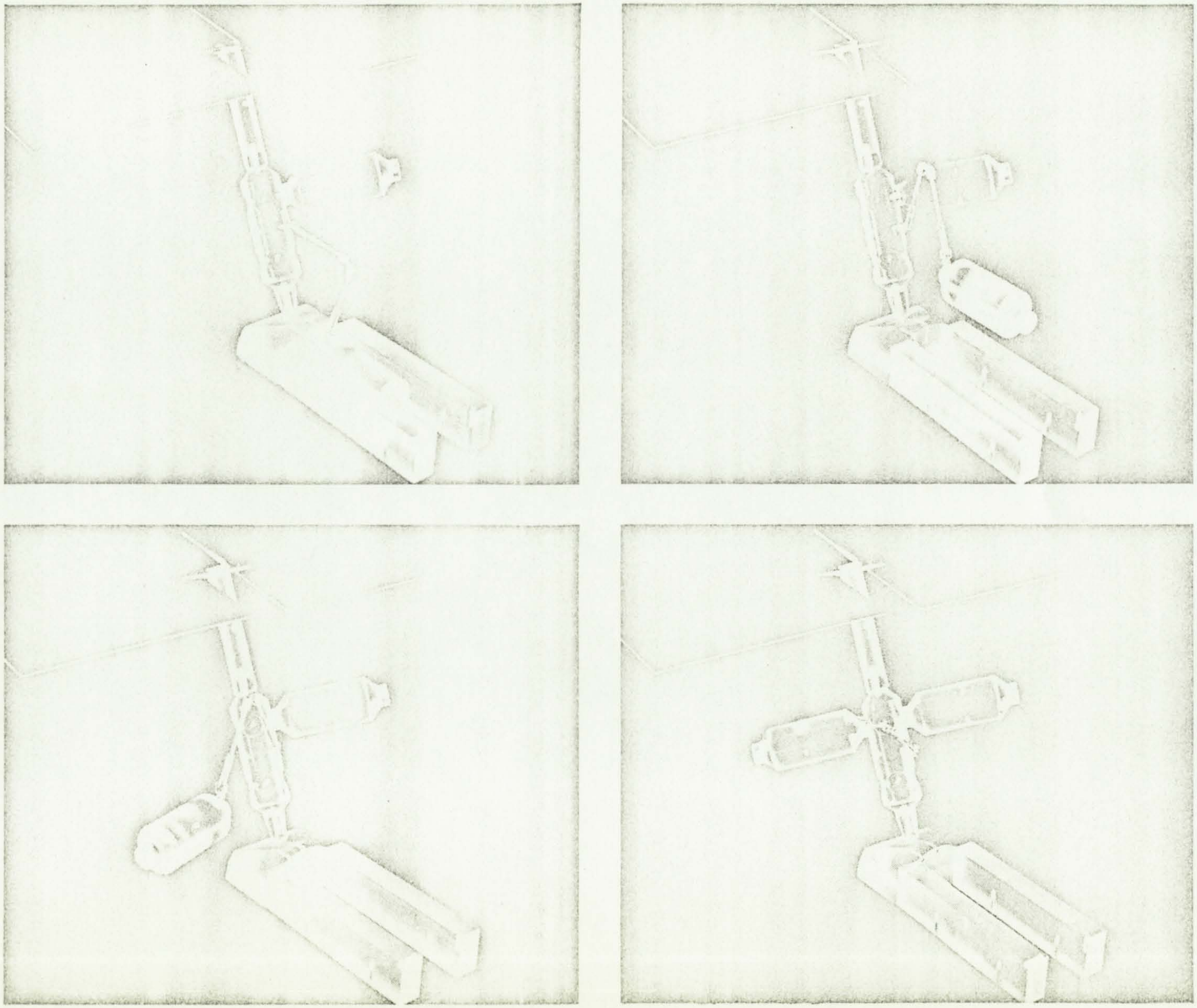


FIGURE 3.5-7
MODULE ASSEMBLY (FORWARD POSITION)

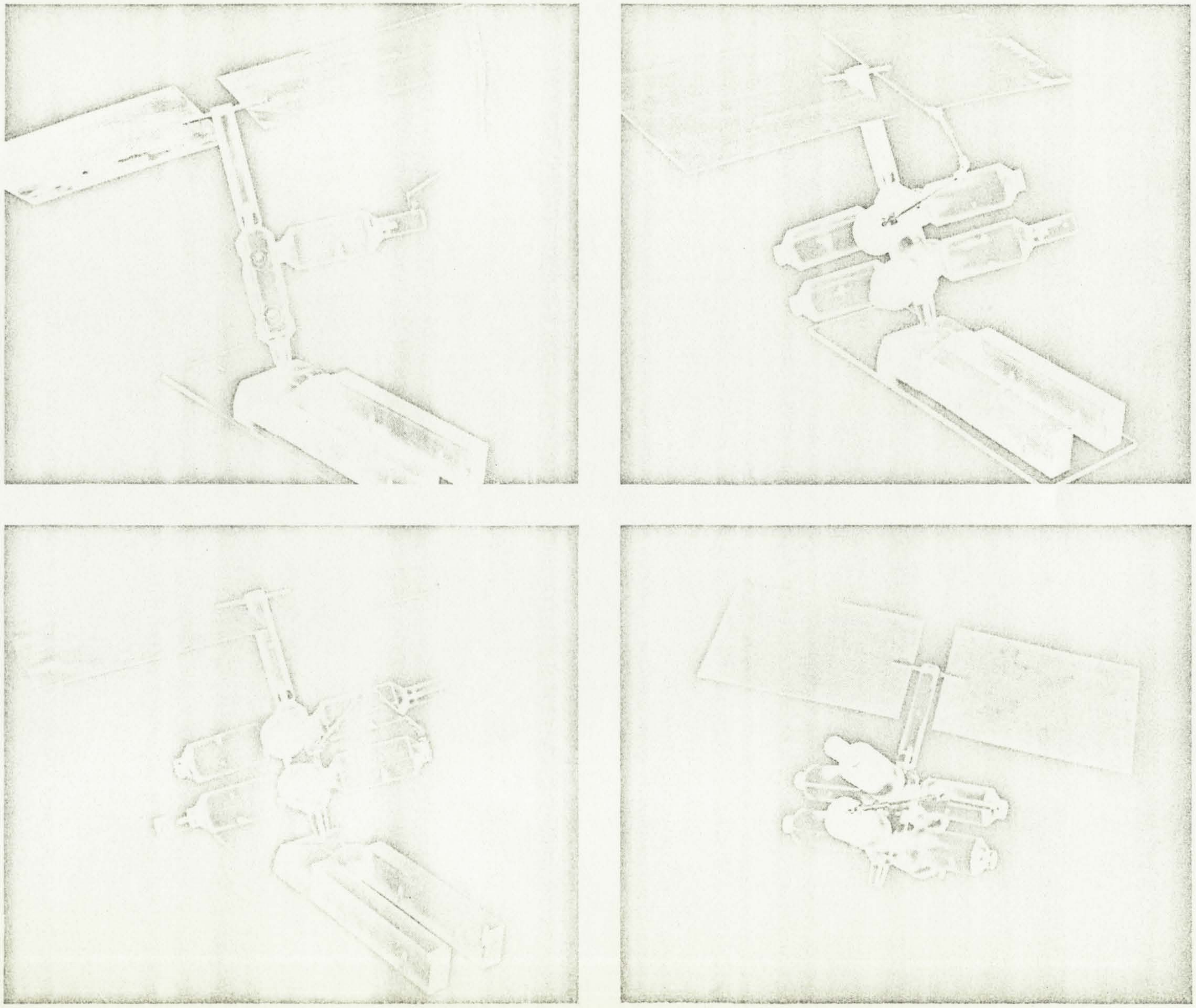


FIGURE 3.5-8
WALKING BOOM AND MAINTENANCE

Figure 3.5-6 shows the crew module being manipulated using the outer root points. Figure 3.5-7 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 3.5-8 illustrates the way in which the boom can walk around the station for inspection, maintenance and repair operation.

3.6 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.

3.7 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 to 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.

4.0 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. The 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.

5.0 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.

6.0 TECHNICAL DISCUSSION

Section 6.0 amplifies in greater detail much of the information presented in Section 3.0 "Results". In general the information presented in Section 3.0 is not repeated so for any subject of interest the reader should first refer to that subject in Section 3.0 if it is included there. The reader should consult the Table of Contents since Sections 3.0 and 6.0 each include subjects not contained in the other.

6.1 Introduction

The present study was divided into Phase I "Concept Development and Selection" and Phase II "Concept Analysis". In Phase I only the minimum analyses and design necessary to compare and evaluate alternate concepts was accomplished. Furthermore, some areas were considered only superficially because they were not fundamental to concept selection, but were equally common to all concepts. The elements appropriate to concept selection and subsequent preliminary design were divided as follows:

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

Although the initial objective of this study was to establish a preliminary design for space station assembly and cargo handling system, it became evident during Phase I that both shuttle and space station applications should be considered simultaneously because of the potential high degree of commonality and resulting development and operational cost savings that could be achieved. Emphasis was therefore placed on maximizing commonality to achieve a general purpose manipulator system suitable for shuttle and space station assembly, docking, maintenance, cargo handling and spacecraft retrieval. The manipulator system areas of commonality between the shuttle and space station include the following:

- Manipulator Booms
- General Purpose End Effectors
- Control and Display
- Data Processing
- Telemetry
- Dedicated Computers
- Control Station Design

The preliminary design resulting from Phase II is described in Sections 2.0 Summary",and 3.0 "Results" and in preliminary design drawings 0053ES0689, 0052ES0690, 0052ES0691, 0052ES0692, 0052ES0702 and 011432. The ground rules established for Phase II 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.

In addition, 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 appendices.

With the exception of the diameter limitation, none of the above ground rules caused undesirable impacts on the manipulator system design. Restricting the diameter to 22.9 cm (9") results in a non-optimum choice of boom thickness and weight. As shown in Section 6.6 below, relaxing the restriction to ~38.1 cm (15") results in a more optimum boom configuration.

6.2 Requirements

The requirements presented below apply to the manipulator system preliminary design established in this study. Quantitative values to these requirements are presented in the pertinent sections elsewhere in this report. Firm quantitative performance requirements are not presented since further detailed analysis and design supported by tests and simulation studies are required to establish them.

6.2.1 General

The tasks to be performed by the shuttle/space station manipulator system are: to assemble a modular space station in earth orbit, to perform station repair and maintenance including replacement of propulsion packages, to assist in berthing the shuttle (shuttle to station or shuttle to shuttle), to unload and load shuttle cargo in orbit and to deploy, service and retrieve satellites. It is anticipated that the manipulator system can also be used in space rescue mission.

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

6.2.2 Subsystem Requirements

6.2.2.1 Manipulator Boom

The boom will have a maximum working force level and deflection determined by the requirement to deploy, manipulate, berth and retrieve shuttle payloads and in addition to assemble, maintain and repair the modular space station. The boom will assist in berthing the shuttle within its force and strength capabilities. In berthing the shuttle, the manipulator shall, upon capture of the shuttle, transmit its boom joint position and rate information to the shuttle such that the shuttle can use its own propulsion/ACS system to bring the shuttle velocities down to levels where the manipulator system can complete the arresting and berthing task. The boom shall be designed to be fail safe. Joints shall not become free if actuators fail.

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

6.2.2.2 Control Station

The manipulator shall be controlled only from primary individual internal control stations on the shuttle and space station. There will be no portable control stations. The manipulator control stations must meet the individual shuttle and space station interface requirements, but at the same time achieve a maximum possible commonality with each other. Except for differences in the crew compartment envelopes and direct viewing capability, it is desired to have identical shuttle and space station manipulator control stations. The manipulator control station will be a modular addition to the control/crew module for the space station. Consideration shall be given to the possibility of time sharing the space station and shuttle computers for manipulator functions.

6.2.2.3 Man/Machine Interface

The operator's control console is the physical realization of the man/machine interface. Detail design requirements are imposed on the console from three main sources; these are: (a) the general control concept, which specifies operator input modes and feedback sources; (b) good human factors practice in console layout and sizing; and (c) specific needs associated with the various interface subsystems, such as TV, computer, etc. These requirements are summarized in Table 6.2-1.

6.2.2.4 Visual System

(1) Viewing Geometry. The system should assure coverage of the entire envelope reached by the manipulator as well as the regions of space adjacent to the envelope in order to provide adequate visual information about objects being manipulated and other nearby structures. The field-of-view presented to the operator shall be large enough so that he can see the manipulated objects' geometrical relationship with such nearby structures and so that he can safely stop the object being manipulated within his field-of-view. Standby optical instruments, such as a dual field variable power (zoom) stereoperiscopes should be available in case of video system failure.

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

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

a) Brightness and contrast control capability
b) Camera mobility
c) Increased resolution (of the order of 1000-1200 lines)

TABLE 6.2-1

MAN/MACHINE INTERFACE REQUIREMENTS

Area	No.	Requirement
A. General	1	One-man operation
	2	Relatively untrained operators
	3	No direct vision (space station)
	4	Direct vision (shuttle)
B. Physical and Antropometric	1	Minimum size and weight
	2	Modular, interchangeable with shuttle
	3	Accommodate 10th to 90th percentile
	4	Restraint without constriction
C. Stereo/Foveal TV	1	Limited central viewing envelope
	2	Adj's. accessible during viewing
	3	Adj. controls "feel" coded
D. Mating & Berthing TV	1	Central position in visual field
	2	Display/control compatibility
	3	Adj's. accessible during viewing
	4	Adj. controls "feel" coded
	5	Visual Alignment Aids Highly Visible and self explanatory
E. Overview TV(s)	1	Position control infrequent
	2	Ref camera position to camera boom attach
	3	Info. on camera boom location
	4	Camera switching matrix
F. Manipulator Configuration	1	Boom angles displayed continuously
	2	Proximity to emergency actuator control

TABLE 6.2-1

(Continued)

Area	No.	Requirement
G. Emergency Control	1	Stop control always accessible
	2	"Dead Man" controls on actuators
	3	Electrical status of manipulator may be required info. during emergency operations.
H. End Effector Mating & Release	1	"Hands On" during mating and berthing
	2	"Mated" status display
	3	Status display proximal to TV
I. Master Arm Controllers	1	Adaptable to all operators
	2	No restraint
	3	Spatial envelope for manipulation is lower-central, good-size, clear of obstructions
	4	Right-hand master converts to stick in convenient location
	5	Masters stow clear of console
J. Computer Communication	1	Comm. central during translation
	2	Proximity to overview TV
	3	Reference for station geometry and nomenclature available
	4	Emphasize "function" buttons, self-guidance, and English language
	5	Input verification
	6	Analog (model) interface well-sized, centrally located, and understandable
K. Operator Communications	1	Connection to other crew members
	2	Audio adj's.
	3	Channel selection

d) Variable field-of-view (zoom)
e) Stereoscopy
f) Eye acuity matching (foveal techniques)
g) Automatic focusing and stereo convergence control
h) Color
i) Specialized visual probes and alignment aids

(4) Visual Display and Controls. Minimum adaptation of the observer to the interface should be provided. The ideal situation would be when the operator could not distinguish between direct observation and the use of the viewing system. The visual displays and controls shall not encumber the operator. Consideration shall be given to head-aiming or eye-aiming camera pointing control techniques which will not interfere with the conscious tasks of the observer. Stereoscopy will provide interfacing with binocular vision. A foveal-peripheral mode should be used to optimize resolution. The controls for stereoscopic convergence and focusing should be either automatic or eye-aimed, in order not to interfere with conscious tasks.

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

6.2.2.5 Control System

The control system shall provide smooth and effective operation of the manipulator boom and supporting equipment. The boom control system will include a computer to interface between the operator and the boom, and it shall continuously monitor the boom operation to assure that it is operated within its load capabilities and operating envelope and that no collisions or unsafe dynamic conditions will occur. The boom control system shall also provide dynamic damping to permit precise acceleration and stopping operations. The boom shall be controlled by a combination end point rate control (without operator force feedback) and force reflecting, position-position end cluster (wrist) control. The dexterous end effector shall have a position-position bilateral force feedback controller. The control modes shall be selected to best meet individual task requirements. The control modes shall include computer supervisory control with the ability to input desired trajectories by use of a sale model controller.

6.2.2.6 Data Processing and Transmission

The data processing and transmission system must process and transmit control signals and instrumentation signals with high reliability and low error rates. The video channels must provide a high signal-to-noise ratio and provide a high resolution view of the work area at all times since it is the primary viewing system. There must be a minimum impact on the station and shuttle by the telecommunication system. The manipulator telecommunication system must be capable of providing relative motion information to the shuttle while the boom is plugged into the station and the shuttle, preparatory to arresting and berthing the shuttle.

6.3 Boom Mechanical Analysis and Design

6.3.1 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 6.3-1)

(4) In the preferred position the three terminator orientor axes should be mutually perpendicular. (See figure 6.3-2)

(5) In the preferred position, the 3 locator or shoulder axes should be mutually perpendicular. (See figure 6.3-3)

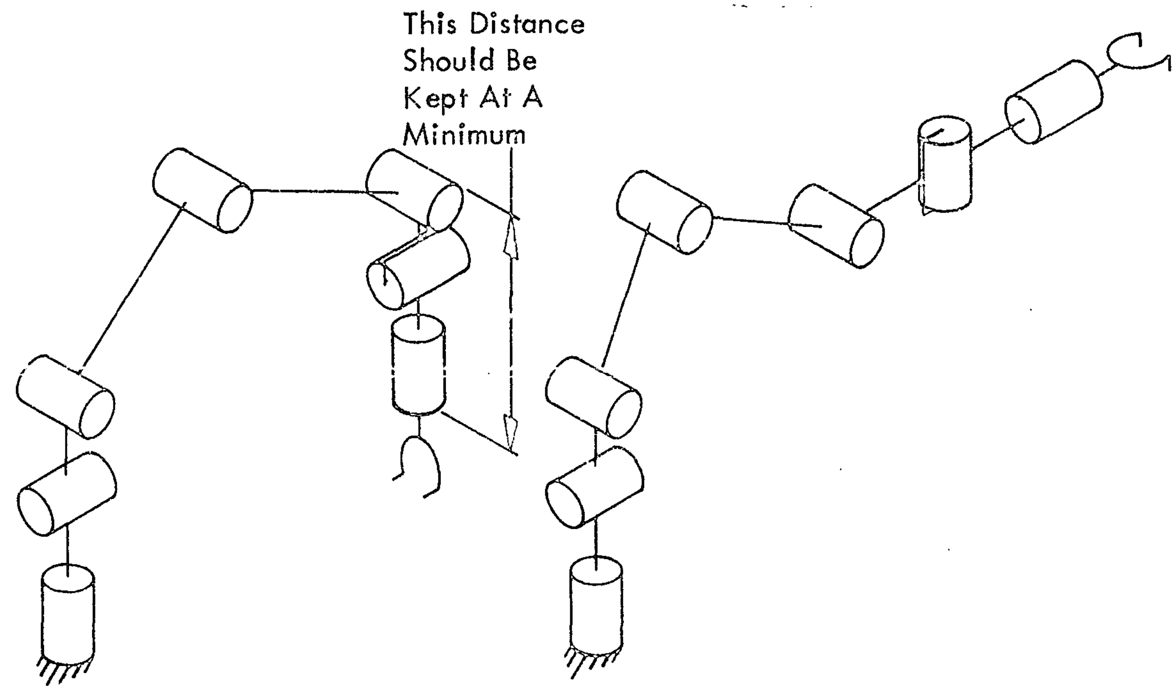
(6) For spot mounted manipulators the actuator connected to the ground should have a vertical output axis. (See figure 6.3-4)

6.3.2 Boom Loads and Structural Analysis

6.3.2.1 Boom Diameter Trade Off

The rationale for establishing the selected boom mechanical design parameters (thickness weight, maximum force and maximum deflection) is given in Section 3.1.3 "Weight and Deflection Trade Offs". The design ground rule that the boom diameter be ≤ 22.9 cm (9") results in inefficient use of the boom wall (tubing) structural material. The arguements presented in Section 3.13 are valid within the given constraints. However, if the diameter restraint is relaxed, a structurally move option configuration can be achieved as shown by the curves given in Figures 6.3-5 and 6.3-6 (these curves are an extension of the curves in Figure 3.1-6 to larger radii).

As the boom radius is increased at constant wall thickness, the deflection and bending stress decrease while the weight increases. (Note the low stress levels - i.e., as stated in Section 3.13, the boom is deflection limited and not stress limited.) As radius extends to infinity, deflection goes to zero for all thicknesses. In other words, as radius is increased, the importance of thickness in reducing deflection is diminished. The locus of constant deflection [(δ=14cm(5.6 in)] shown in Figure 6.3-6 shows however that if deflection is held constant, the weight of the boom decreases (thickness decreases) as radius increases. A more optimum radius selection criteria is therefore to establish (1) the maximum allowable deflection and (2) the minimum practical wall thickness based on fabrication (thickness required for riveting, threads, welding, etc.), ruggedness (collisions, abuse, etc.) and structural shape availability (standard tubing sizes available, cost of new tooling, etc.). Such a radius selection criteria must be used in the context that: (1) there is room available to accommodate the selected radius (stowage volume in the shuttle for example) and (2) the selected radius does not diminish or encumber the



Good Design

Clumsy Design

FIGURE 6.3-1
RULE III ORIENTOR AXES LOCATION

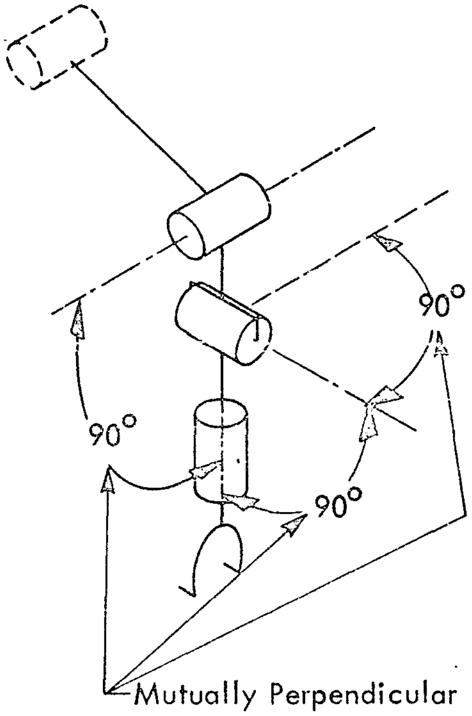


FIGURE 6.3-2
RULE IV PERPENDICULAR ORIENTOR ACTUATORS
FOR NORMAL OR PREFERRED POSITION

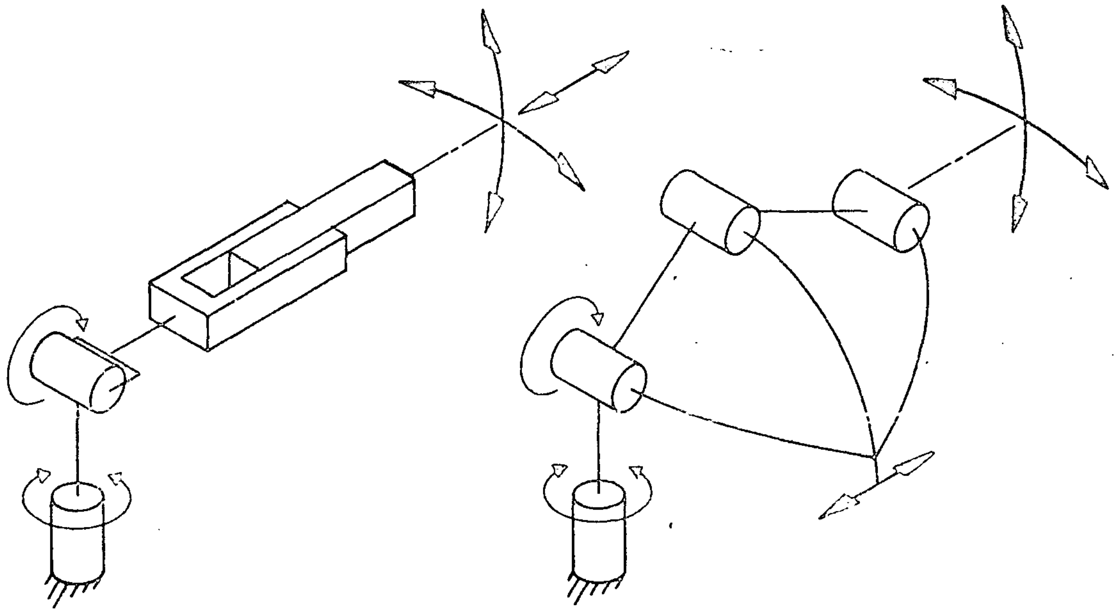


FIGURE 6.3-3
RULE V MUTUALLY PERPENDICULAR LOCATOR ACTUATORS

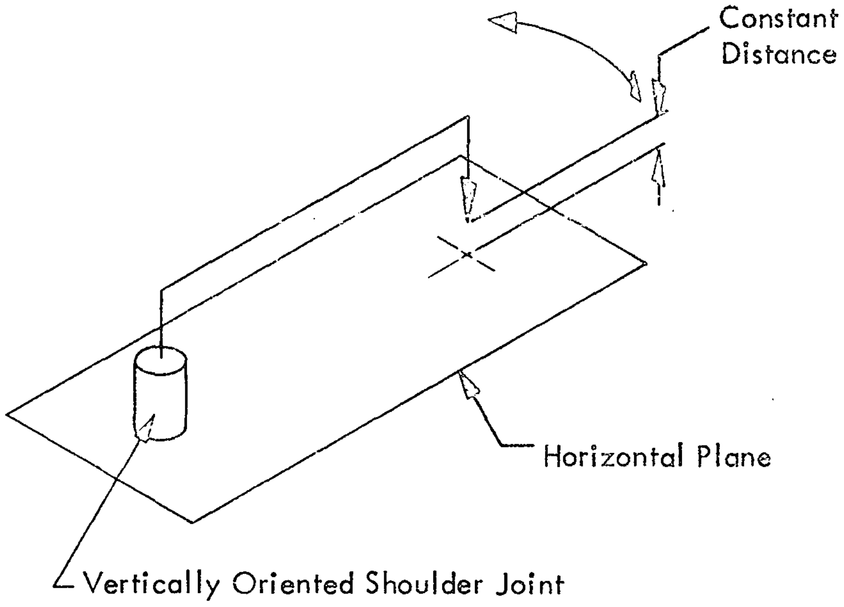


FIGURE 6.3-4
RULE VI HORIZONTAL TIP MOVEMENT
(SPOT MOUNTED MANIPULATORS)

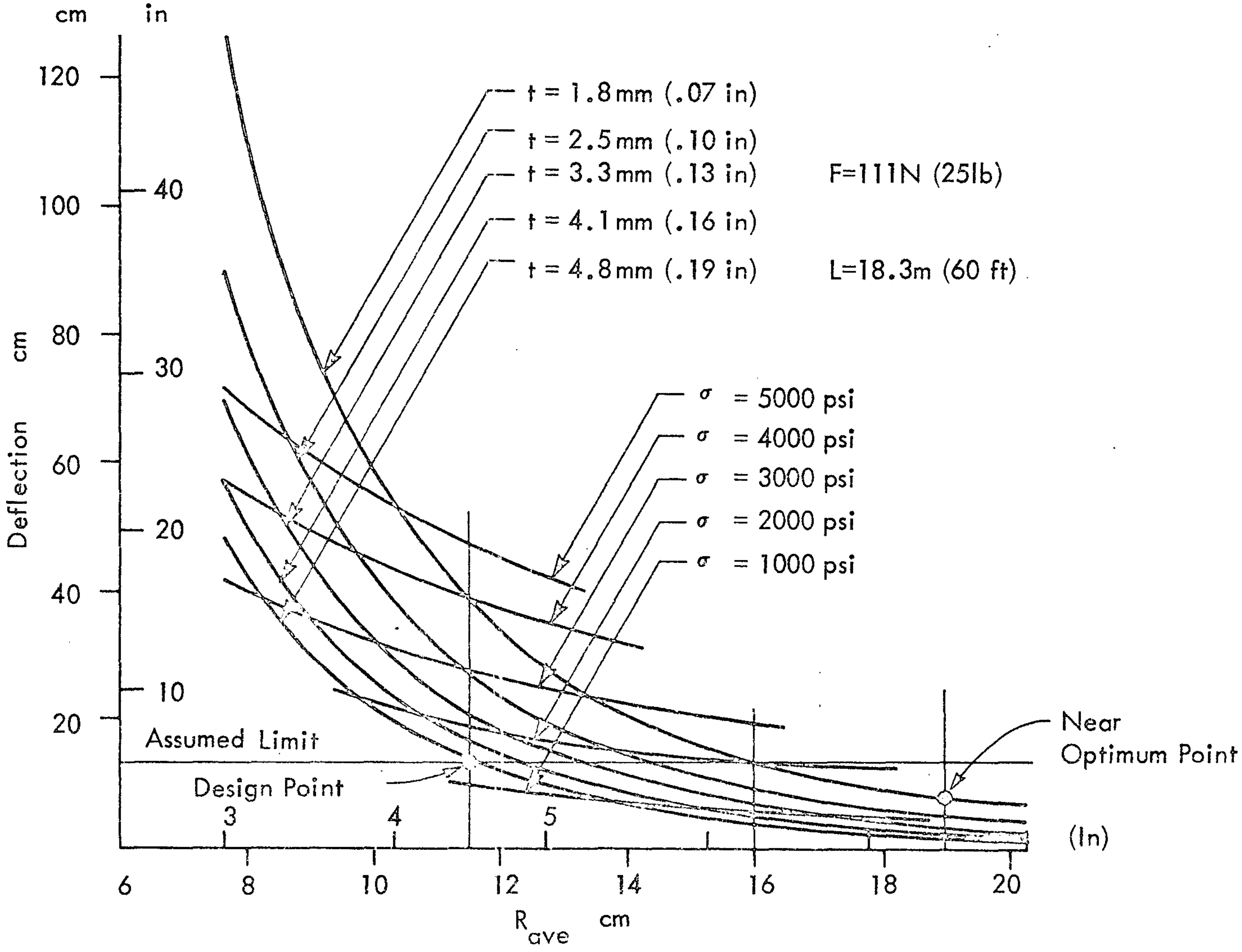


FIGURE 6.3-5.
DEFLECTION TRADE OF CURVES FOR ALUMINUM BOOM

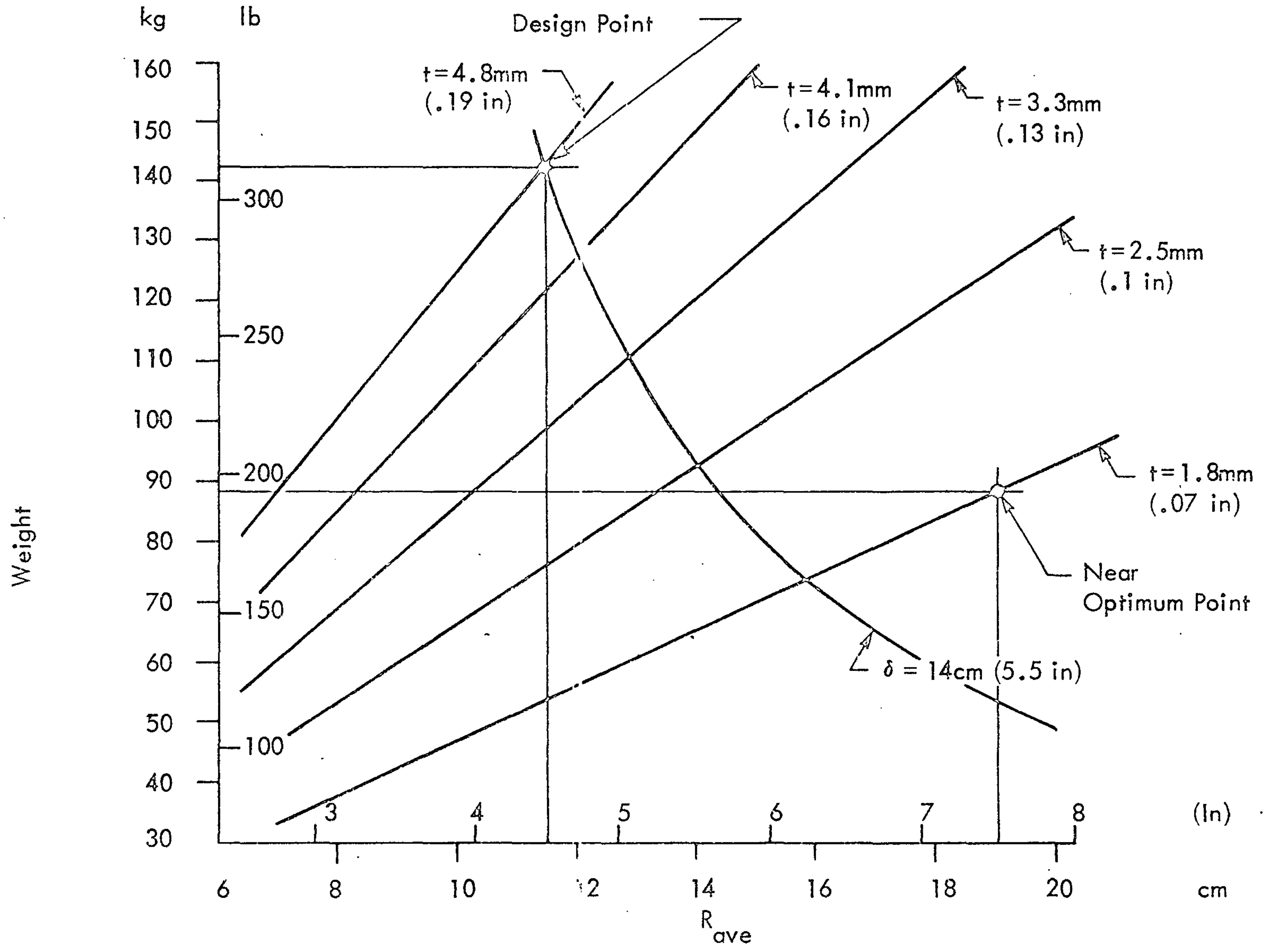


FIGURE 6.3-6.
WEIGHT TRADE OF CURVES FOR ALUMINUM BOOM

dexterity and usefulness of the boom (i.e., diameters too large will restrict the possible joint range of motions and interfere with accessing small work areas). On these bases and assuming aluminum as the structural material, a wall thickness of ~1.8mm (.070 in) and a radius of ~19cm (7.5 in) appears as a more nearly optimum boom design. Compared with the selected reference design, it offers:

(1) reduction in weight from 144 Kg (316 lbs) to 88 Kg (195 lbs)

(2) reduced maximum deflection to 8 cm (3.1 in) (radius could be reduced so that $\delta_{max} = 14$ cm (5.6), however a 19 cm (7.5 in) radius appears to be a better choice of the "point of diminishing returns")

(3) reduced stress levels making the use of beryllium more practical (i.e., crack sensitivity effects are reduced at lower stress levels - see Section 3.1.3)

The potential improvements offered by increased boom diameter warrant serious consideration of increasing the available boom storage volume on the shuttle.

6.3.2.2 Mechanical Design Parameters and Stress Margins

The mechanical design parameters of the selected boom configuration are as follows:

<u>Geometry</u>

Total length (L) = 18.3m (60 ft)
Wrist/Shoulder length = 1m (39 in)
Arm length = 8.15m (26.7 ft)
Diameter (d) = 22.9 cm (9 in)
Wall thickness (t) = 4.8 mm (.19 in)
Cross Sectional Area (A) = 34.2 cm^2 (5.3 in^2)

Structural Material

Al 6061-T6
Density (ρ) = 2.78 g/cm^3 (.1 lb/in^3)
Bending Modulous (E) = 6.9x10^{10} Pa (10^7 psi)
Shear Modulous (G) = 2.6x10^{10} Pa (3.8x10^6 psi)
Ultimate Tensile Strength (σ_u) = 3.1x10^8 Pa (4.5x10^4 psi)
Yield Tensile Strength (σ_y) = 2.8x10^8 Pa (4.0x10^4 psi)
Tensile Endurance Limit (σ_e) = 9.7x10^8 Pa (1.4x10^4 psi)
Ultimate Shear Strength (τ_u) = 2.1x10^8 Pa (3.0x10^4 psi)
Yield Shear Strength (τ_y) = 1.4x10^8 Pa (2.0x10^4 psi)

Structural Characteristics

Bending Sectional Modulous (I) = 2560 cm^4 (52 in^4)
Shear Sectional Modulous (J) = 5120 cm^4 (104 in^4)
Bending Stiffness (K_B) = 82 Kg/m (55 lb/ft)
Torsional Stiffness (K_T) = 1090 Nm/deg (811 ft-lb/deg)

The fundamental vibrational characteristics of the boom are discussed in Section 3.1.4 with the exception of end on loading, boom impact loads have not been analyzed in detail because capture, translational, and closure velocities are low $\leq$ .12m/sec (.4 fps) and the boom is protected from overloading by the computer control system and the actuator slip clutches. Worst case loadings occur with the boom extended straight out or bent at right angles at the root point. The maximum bending and torsional moments for these cases are the same and equal to 2030 Nm (1500 ft-lb). The resulting bending stress is shown in Figure 6.3-5 to be ~ 1.1x10^7 Pa (1600 psi). The maximum shear stress due to normal side loading of F/A = 3.3x10^4 Pa (4.7 psi) is insignificant. The torsional shear stress $\sigma_s = \frac{Tr}{2J}$ = 5.5x10^6 Pa (790 psi). The maximum combined bending and shear stress and stress margin resulting from the above stresses are as follows:

Stress	Maximum Combined Value	Margin On Endurance	Margin On Yield
Bending	1.22×10^7 (1780 psi)	7.9	22.5
Shear	6.12×10^6 (890 psi)	7.9	22.5

The high margin (factors of safety) again show that the boom is deflection limited and not stress limited.

The most critical loading access for a "stiff arm", (boom straight out) end on collision. In this case the kinetic energy of the moving object must be absorbed by axial compression of the boom or:

$$KE = \frac{F^2_{max} L}{2\ EA}$$

The critical column buckling load for the selected boom is given by the equation

$$F_{cr} = \frac{\pi^2 EI}{L^2} \quad = \quad 4.8\times10^4\ N(1.1\times10^4\ \text{lbs})$$

The case of the mini-shuttle colliding end-on with the straight out boom is as follows:

Impact Velocity	F_{max}	σ_i/σ_{impact}	F_{cr}/F_{max}
.12 m/sec(.4 fps)	15.2×10^4 (34.4×10^3 lb)	6.2	.31 (buckling)
.03 m/sec (.1 fps)	3.8×10^4 N(8.6×10^3 lb)	25	1.25

If the impact load was evenly distributed, the boom(end connector) would not be damaged. However, such is not likely to be the case and furthermore it is not likely that the shuttle could withstand such a blow [15.2×10^4 (34.4×10^3 lbs)] without damage. Capture procedures must be established to avoid such a situation.

6.3.3 Actuators

A description of the selected actuator configuration and the design criteria used to select it is given in Section 3.1.1 "Actuators". The range of motion required of the actuators is shown in Figure 2.3-3, Section 2.3 "System Description".

A DC drive motor was selected because of its ease and range of control and because it is compatible with both the shuttle and space station power systems. The types and characteristics of the various drive motors considered are summarized in Table 6.3-1. Specifically a shunt type DC motor was selected because of its highly developed state-of-the-art, high specific power, small size, and good efficiency. The following ten different types of DC electric motor driven actuators were considered:

(1) Spur Gear Train
(2) Serpentuator Compound Linkage
(3) Harmonic Drive
(4) Ball Screw/Linkage
(5) Hydraulic Cylinder/Linkage
(6) Hydraulic Cylinder/Silent Chain
(7) Cone Drive Gear
(8) Double Cone Drive Gear
(9) Internal Spur Gear
(10) Planocentric Double Differential Gear

The planocentric Double Differential Gear Actuator configuration was selected because of its:

(1) Compact size and low weight

(2) Compatibility in shape and range of motion for use in both pivot and roll joints

(3) Redundant arrangement of two parallel motors and drive trains (reliability)

(4) Ability to eliminate back lash by stopping the double drive gears slightly out of phase (i.e., working against each other)

SHUNT DC MOTOR - G.E. REGEN BRAKING, COMPLICATED, EFFICIENT
DIRECT DRIVE DC TORQUE - INLAND-SPACE QUAL., HIGH TORQUE, HIGH WEIGHT
BRUSHLESS - SPERRY REGEN. BRAKING, COMPLICATED, LONG LIFE, DEVELOPMENTAL

	P_o (HP)	T (Ft-Lb)	n (RPM)	W (Lb)	E (%)	HP/LB	T/LB
G.E. 5 BA50 SHUNT	.5	.525	5000	10	74	.05	.05
PMI V12	.2	.287	3650	8	70	.025	.036
SPERRY	.48	.27	10,000	15	65	.032	.018
BENDIX	.008	.85	52.5	3.06	18	.00277	.277
SLO-WYN SS250	.0142	1.25	60	6.5	30	.0022	.193
SERVO TEK SU680D	.0163	.01	8600	.5		.032	.02
GLOBE MM	.01	.0025	16,000	0.22		.045	.0113
KEARFOTT 400 HZ 18	.0117	.025	9800	1.25	25	.0093	.02
SIEMENS	.003	.002	8000	.4	45	.0075	.005
AIRESEARCH LRV	.15	1.	4000		75		
AIRESEARCH BRUSHLESS	.0134	.0135	5000	2.25	75	.006	.006
INLAND T-7202	.11	11.	220	10.3	50	.0106	1.06

TABLE 6.3-1
CANDIDATE ACTUATOR MOTOR TYPES

(5) Good overall efficiency (~70%)

(6) Hermetically sealed motor and high speed drive train (no oil leakage)

(7) Ability to separate the functions of the heavily loaded eccentric drive and of the flexible bellows seal.

(8) Reduced output gear tooth load achieved by the ability to have wide teeth of ideal form and by spreading the load over many teeth.

The spur gear train was eliminated because of its large weight (poor structural use of gears because of 1 point loading). The serpentuator type double linkage (it is capable of ± 180° so that the arm elements of a joint may fold back on themselves) was ruled out because it is not adequate for roll motion about the boom axis and because it appeared heavy.

The Harmonic drive actuator is used in a variety of applications including satellites. It was therefore given serious consideration because it is well developed and compact. Harmonic drives appear well suited to light load applications, however, where repetitive heavy loads and/or long life requirements are encountered, such as may be the case with the main boom actuators for the present manipulator system, cracking of the flexible spline member may become a problem.

This concern was expressed by personnel at the Western Gear Manufacturing and it appears to be supported by experience gained in developing the NERVA reactor control drives as stated by Mr. V. Winters (now with PAR) who was responsible for their development. Accordingly, harmonic drives were ruled out since, as described in Section 3.1.1, the advantages of a harmonic drive (compact size, high gear ratio and the possibility of a sealed drive motor) can be obtained with a planocentric differential gear train without incurring the possible fatigue problems resulting from a flexible spline.

Schematic illustrations of actuator drives (4) through (9) are shown in Figures 6.3-7, -8 and -9. Actuator (10), the selected differential gear train is shown in Figure 2.3-2. The ball screw/linkage actuator [Figure 6.3-7(a)] consists of electric motors driving a gear box and ball screw which thus forms a linear actuator. The linear actuator then operates a 4-bar linkage which converts the linear motion to 180° of output rotation with minimal torque variation (within $\pm \sim 10\%$). The disadvantage of the ball screw/linkage actuator is the low effective reduction through the linkage due to the pitch of the ball screw. A reduction of about 16:1 seems practical which would have required heaving gearing in the reduction to the linear actuator. It is also a long actuator (not well suited for use in the roll joints) and the slip clutch would have to be in the linear actuator (the ball screw nut) since the actuator may not be back driveable beyond that point. The ball screw/linkage actuator was therefore ruled out.

The characteristics of the remaining actuators are summarized in Table 6.3-2. (Note that the Internal Spur Gear and Double Differential Gear actuators are sized for a 111 N (25 lb) tip force. Comparison of the 22 N (50 lb) 4-motor Double Differential Gear actuator with the 111 N (25 lb) Double Differential Gear actuator indicates the approximate weight and size scale factors to use to compare all actuators in the table.)

The hydraulic cylinder/linkage actuator uses the same linkage as the ball/screw/linkage actuator. The pump(s) are built into the actuator, so no hydraulic lines penetrated the package and the hydraulic cylinder/piston rod is hermetically sealed with a bellows [see Figure 6.3-7(b)]. Two electric motors, two pumps, two servo valves, and backup seals in the cylinder are used for redundancy. The servo valve(s) are pressure control type which provide a backdriveable system and overload protection. A 3000 psi system pressure is used.

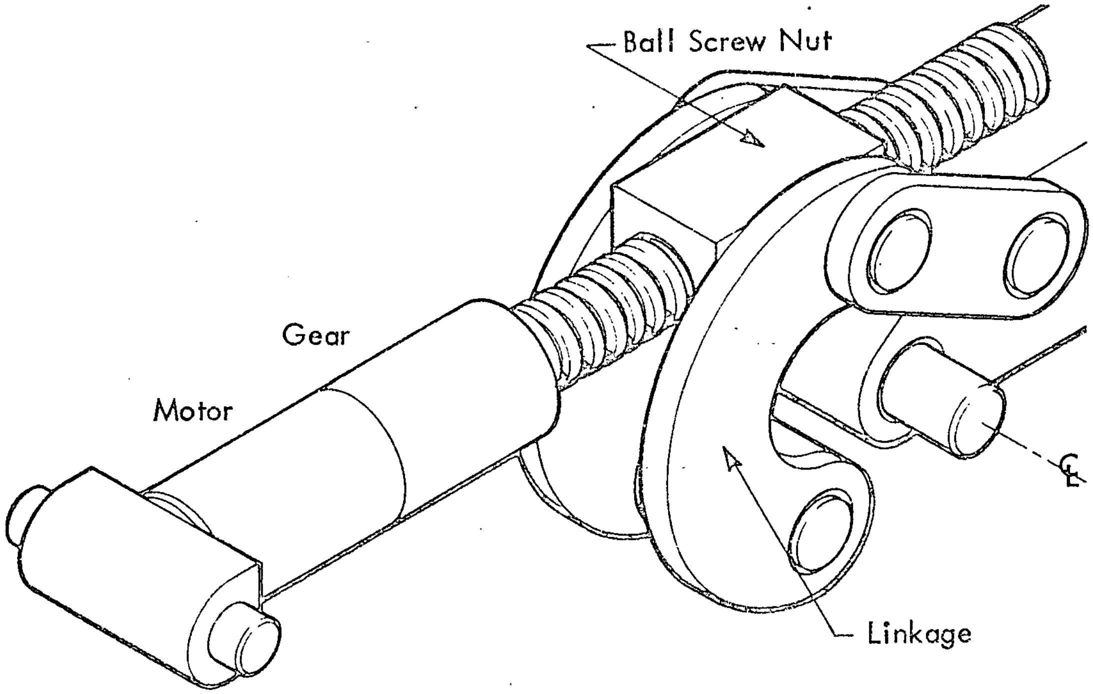
As shown in Table 6.3-2 the disadvantages of this actuator configuration are a long envelope and the inherent possibility of leakage. Furthermore detailed analysis indicates no weight advantage over other actuator configurations.

Name		Hyd/ Linkage	Hyd Silent Chain	Cone Drive	Double Cone Dr.	Differential Gear, 4 Motor	Internal Spur Gear	Double Diff. Gear
Tip Force	kg	22.7	22.7	22.7	22.7	22.7	11.4	11.4
	(lb)	50	50	50	50	50	25	25
Overall Size	m	.22 X .18 X .63	.55 X . 18 X .19	.18 X .15 X .32	.18 X .18 X .32	.25 Dia X .25	.3 Dia X .23	.23 Dia X .18
	(in)	8.5 X 7 X 24.7	21.5 X 7.25 X 7.5	7 X 6 X 12.5	7 X 7 X 12.5	10 Dia X 10	12 Dia X 9	9 Dia X 7
Length ℄ To Back	m	.51	.48	.23	.23	.13	.15	.11
	(in)	20	19	9	9	5	6	4.5
Weight	kg	21.4	23.6	24.5	27.3	21.4	12.7	11.4
	(lb)	47.0	52.0	54.0	60.0	47.0	28.0	25.0
Rotation Range		180°	Drawn @ 180°	Continuous	Continuous	Continuous	Continuous	Continuous
Envelope Compat. Pivot		Long	Long	Good	Good	Good	Good	Good
Envelope Compat. Roll		Bad	Bad	Med. Bad	Med. Bad	Good	Good	Good
Eff. $\frac{\text{Mech Out}}{\text{Mech In}} \times 100$		10-80 %	10-80%	30-35%	30-35%	50-55%	70%	70%
Backlash @ Boom Tip,	m	$3(10^{-3})$	0	$6\ (10^{-3})$	0	$6(10^{-3})$	0	0
	(in)	.12	0	.24	0	.24	0	0
Reliability		Dual Motors/Pumps Seals	Dual Motors/Pumps Seals	Dual Motors	Dual Motors & Gears	4 Motors + 4 Hispd. Gears	Dual Motors & Spur Gears	Best Everything Dual
Oil/Fluid Leakage		Possible-Cyl. Rod Boots	Possible-Cyl. Rod Boots	0	0	0	0	0

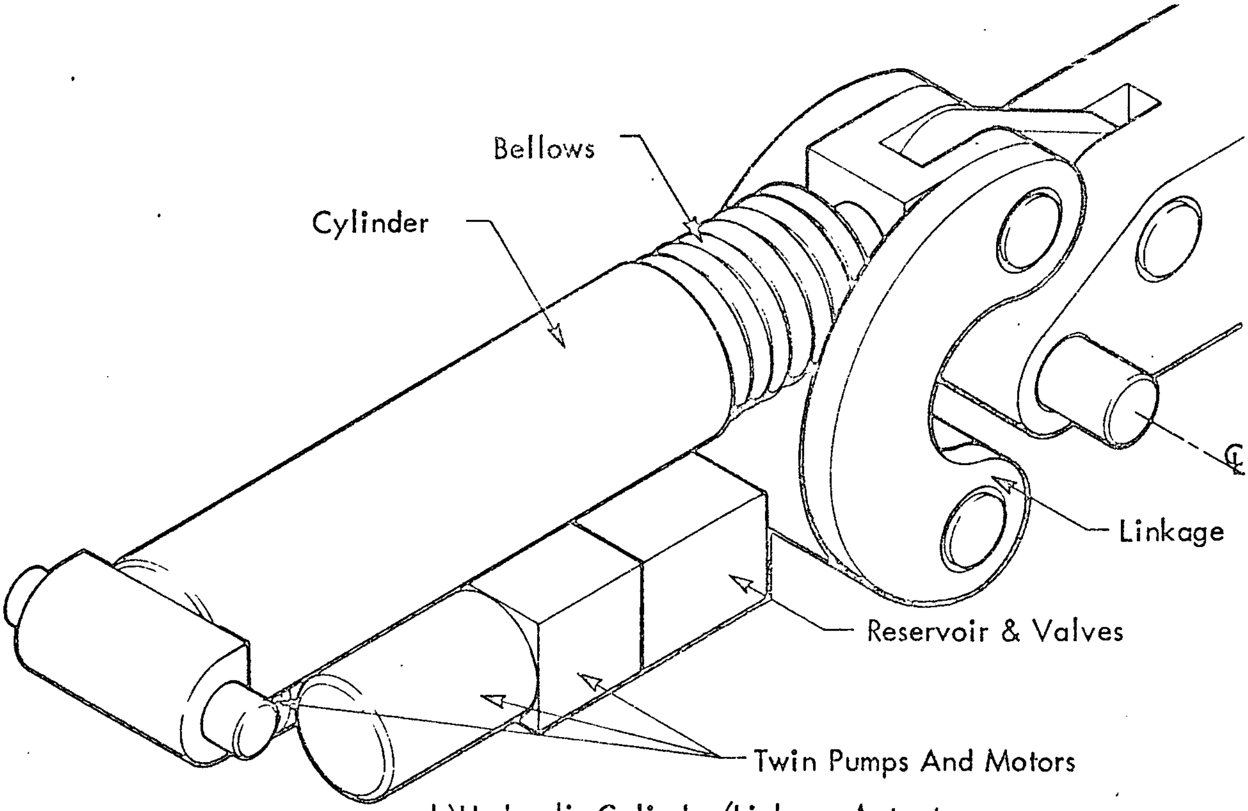
(1) Distance From Pivot Axis Of Joint To Extreme End (Back) Of Actuator.

(2) Boom Envelop Compatibility.

TABLE 6.3-2
ACTUATOR WEIGHT, SIZE AND FUNCTION COMPARISON



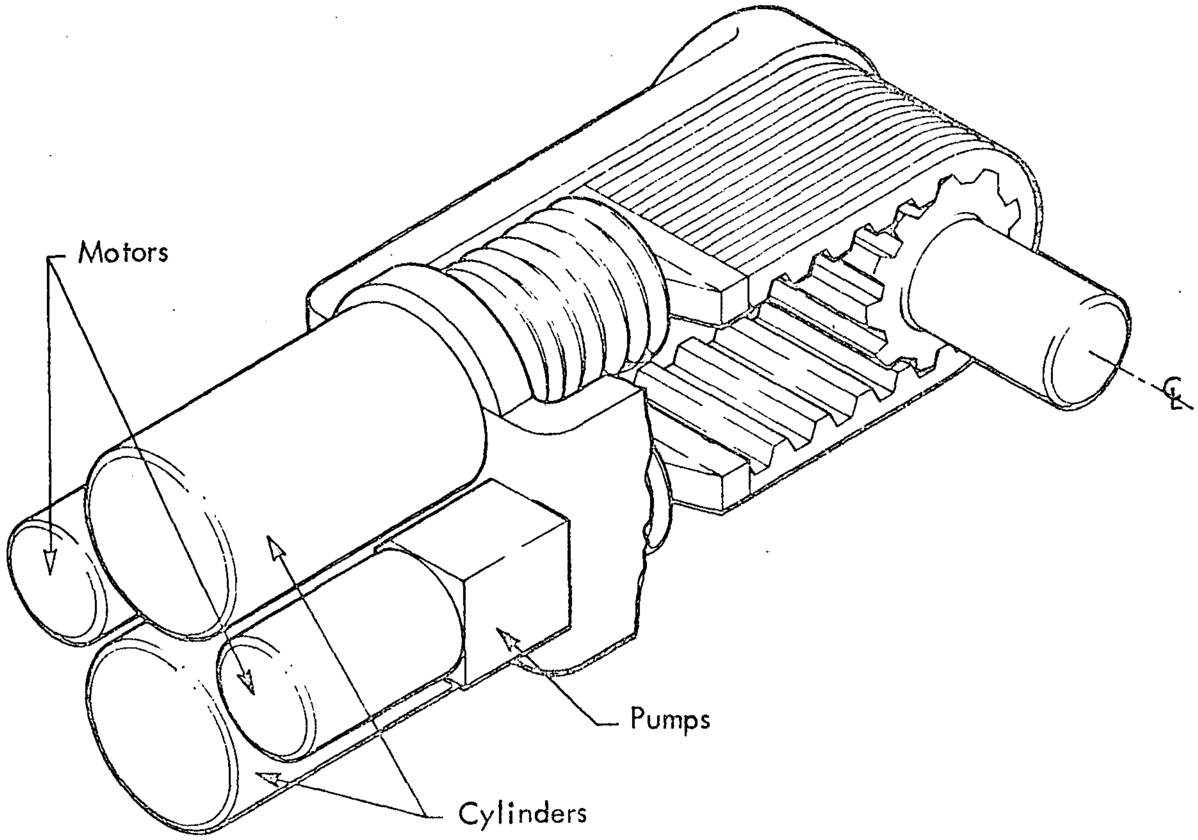
a) Ball Screw/Linkage Actuator



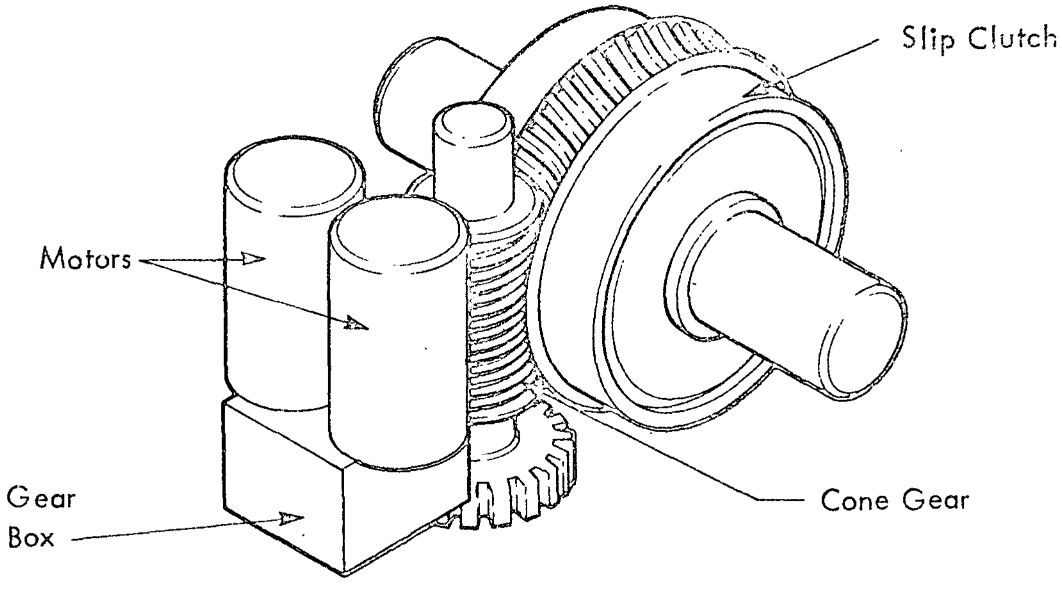
b)Hydraulic Cylinder/Linkage Actuator

FIGURE 6.3-7
LINKAGE TYPE ACTUATORS

3351-9883

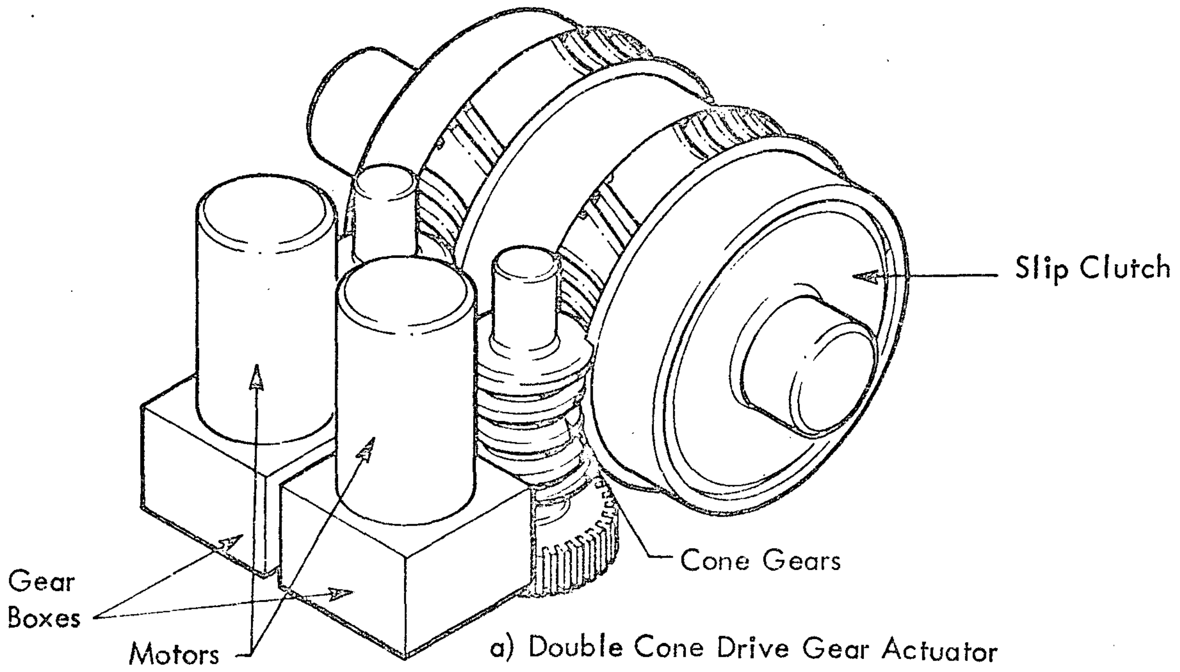


a) Hydraulic Cylinder/Silent Chain Actuator

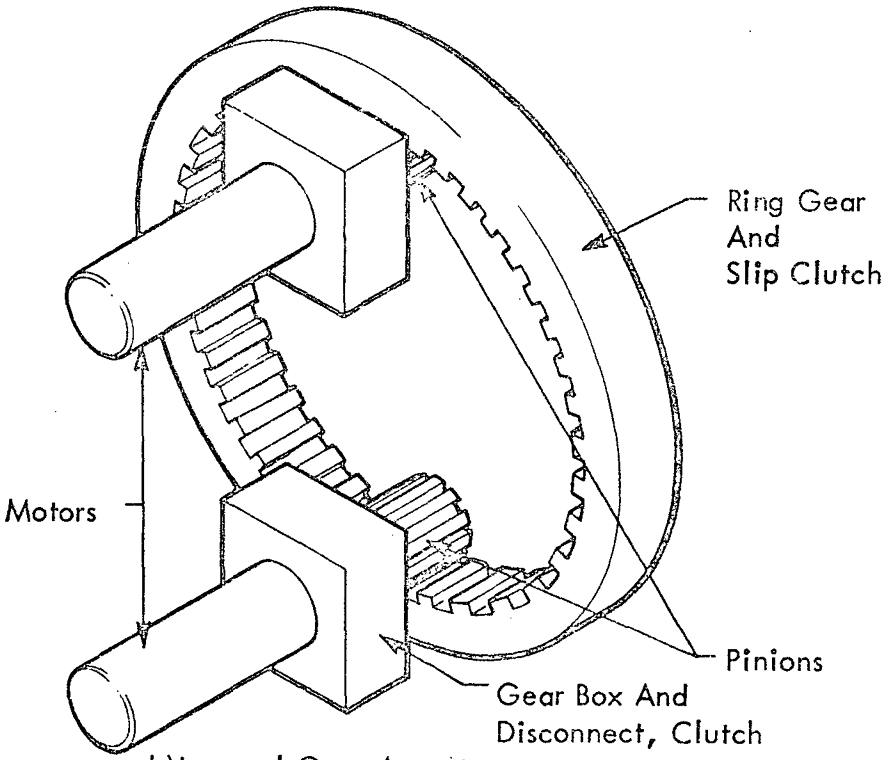


b) Cone Drive Gear Actuator

FIGURE 6.3-8
CHAIN AND SINGLE CONE GEAR ACTUATORS



a) Double Cone Drive Gear Actuator



b)Internal Gear Actuator

FIGURE 6.3-9
DOUBLE GEAR DRIVE ACTUATORS

The hydraulic cylinder/silent chain actuator shown in Figure 6.3-8(a) employs a wide silent chain actuated by two single acting cylinders keeping the chain in tension. Redundancy and control and hermetic sealing are similar to the hydraulic cylinder/linkage actuator. The length of the silent chain actuator is somewhat smaller than the hydraulic cylinder/linkage actuator but weight is about the same. Neither hydraulic actuator configuration can approach the envelope requirements of the roll motions.

The cone drive gear actuator is a compact configuration utilizing a 50:1 cone drive gear set with a slip clutch buried in the outer gear. Compared to spur gears, cone drive gears have a high strength to weight ratio because the double enveloping worm allows each revolution of the worm to engage the gear. [See Figure 6.3-8(b)]. By placing the worm vertically on the boom's center axis and the motor parallel to the worm, only the output gear dictates the profile at the output shaft. However for roll actuators the motor and worm gear assembly will protrude outside of the boom envelope. A backlash of ~.001" can be attained by close gear finishing; with adjustable centers, it could be reduced to almost zero. Dual electric motors, with failure declutchers are fed to a single hi-speed reducer which is coupled by spur gears to the worm. A multiple disc slip clutch is used, rather than a cone clutch, because it will allow for some dimensional change. The weight of the cone drive gear actuator is slightly higher than other candidates, its efficiency is lower and it is not as compact as the differential or internal spur gear configurations.

The double cone drive gear actuator uses essentially the same components as above except two complete gear trains were used to eliminate backlash [see Figure 6.3-9(a)]. The disadvantage is a 20% weight increase.

The internal spur gear actuator is comprised of two motors and gear trains driving a ring gear. Its advantages are short length to diameter ratio, so that it can be used for roll motions with no envelope protrusions. It was also most efficient because of the spur gear train, and has no backlash because of the dual input drive. However, relative to the differential gear actuators it is heavier because of the large gear teeth necessary since only a few teeth are in contact [see Figure 6.3-9(b)].

6.3.4 Thermal Analysis

Approximate thermal analyses were made to identify important thermal design requirements for the boom. Specifically, the question of thermal control for the actuator/control components contained within the boom and of the possible magnitude of overall boom thermal distortion were considered as described below.

6.3.4.1 Thermal Control

A typical array of actuator/control components in a boom joint is illustrated in Figure 6.3-10. As shown below:

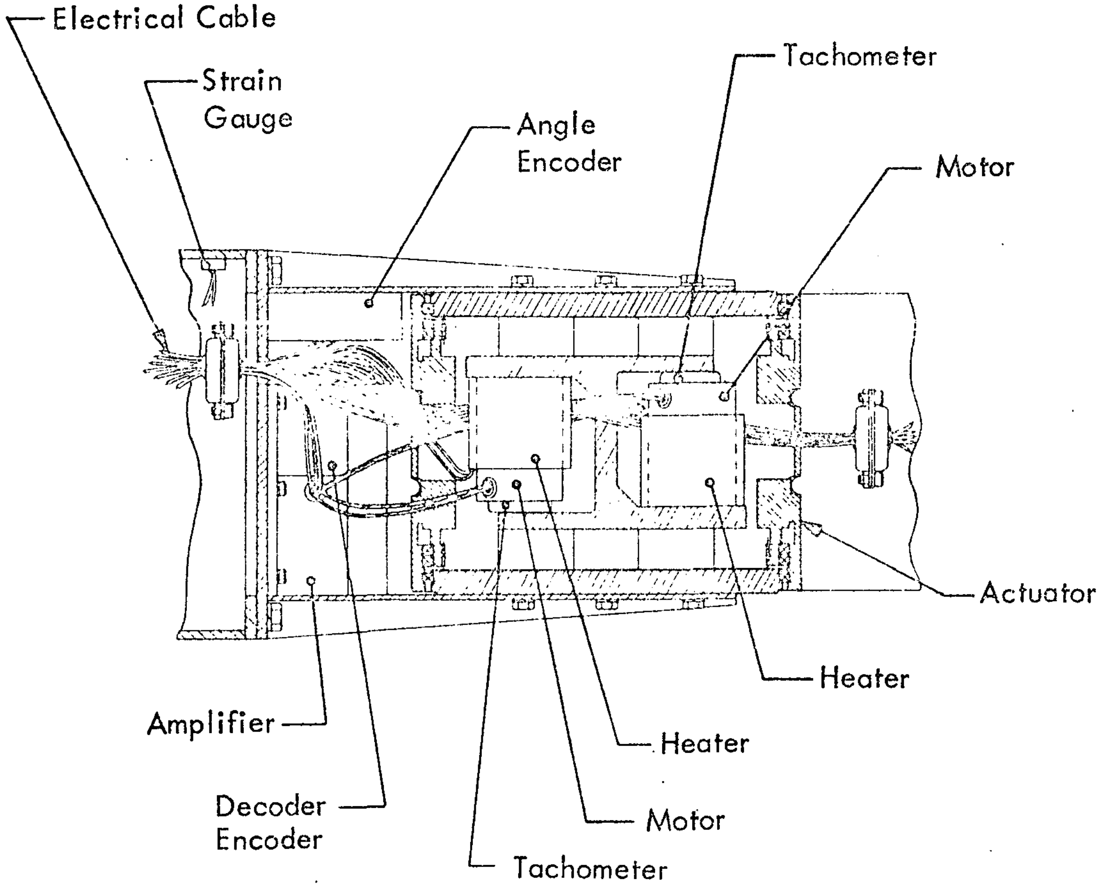


FIGURE 6.3-10.
SCHEMATIC ARRANGEMENT OF JOINT COMPONENTS

Thermal control must be provided for reliable operation of the electronic and motor components since they will not function properly unless they are kept within the temperature between -50°C and 200°C (-58°F and 392°F). In order to accomplish this it is important that the boom at all times be below 200°C (392°F). Should the boom go below -50°C (-58°F) it would be acceptable, for heaters can easily be added to the components. It is much more difficult, however, to cool the components if the boom is above 200°C (392°F).

Since the precise orbit of the Space Station is not known at this time a worst case was considered. A 370 Km (230 mile) high circular orbit with the orientation such that the sun is always hitting the manipulator (See Figure 6.3-11). Furthermore, the axis of the boom was assumed to be perpendicular to the sun and earth vector at all times. To simplify the computer program used to analyze the thermal problem, the boom was approximated as a 18.3m (60 ft) long by 22.9cm (9 in) square tube.

The radiant energy inputs are solar radiation, earth-shine and earth albedo. The sum of the incoming radiation must equal the average outgoing radiation so that:

$$q_s + q_e + q_a = q_r$$

or

$$\int \alpha \, (q_s + q_e = q_a) \; dA = \int \varepsilon \sigma T^4 dA$$

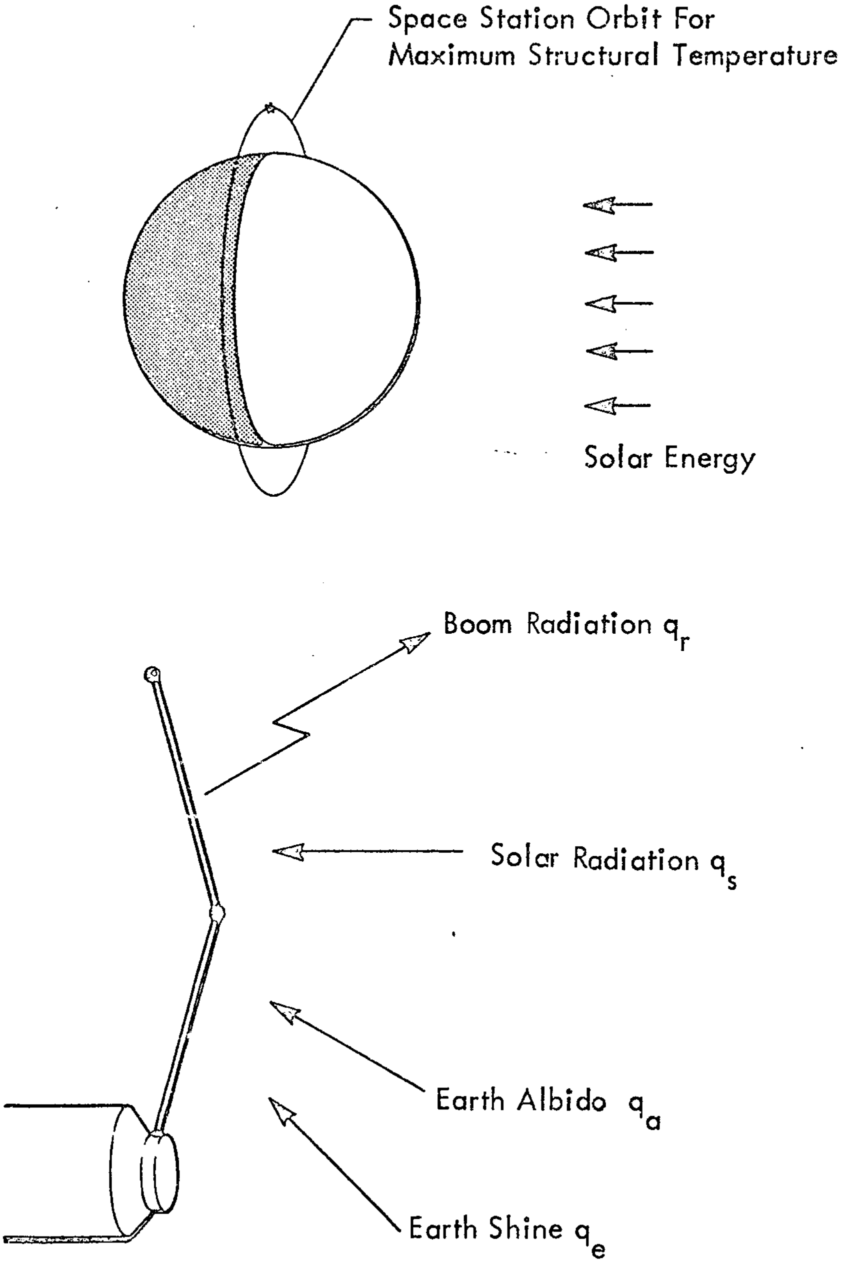
From a computer calculation, the following values were obtained.

$$556 \alpha = 4 \varepsilon \sigma T^4 \; (T = {}^{\circ}R)$$

For black paint $\frac{\text{Absorptivity}}{\text{Emissivity}} = \frac{\alpha}{\varepsilon} = 1.04$. Substituting this in the above equation yields:

$$T = 299^{\circ}K \; (538^{\circ}R) = 26^{\circ}C \; (78^{\circ}F)$$

This temperature is well below the maximum 200°C allowed and if the orbit of the manipulator is such that it is shaded by the earth part of the



$$q_e + q_a + q_s = q_r$$

FIGURE 6.3-11
ASSUMED ORBIT AND BOOM GEOMETRY FOR THERMAL CONTROL ANALYSIS

time, then the average temperature will be lower. However, heaters can be added to keep the components warm enough.

The amplifiers have heat sinks attached. However, the exact size cannot be determined until the orbits have been determined. It is felt that the heat from both the amplifiers and motors can be conducted to the boom tubes and from there it can be radiated away. Also, since the actuators are used for a short duration each time, the thermal capacitance of the structure should be enough to keep the amplifiers and motors cool. A maximum of 32 watts would have to be dissipated from each amplifier and about 22 watts from each motor when they are run at maximum loading.

6.3.4.2 Thermal Deformations

Similar to the above analysis a worst case model was assumed to investigate the maximum possible thermal distortion of the boom. It was assumed that all of the solar energy enters along one side of the boom and that the boom consists of two half-circles at temperatures T_1 and T_2. Energy is exchanged between the two half-circles by conduction and radiation. For heat conduction it was assumed that the energy passes from the midpoint of one half-circle to the middle of the other. This assumption tends to give a temperature gradient larger than it would actually be.

The following equations were solved numerically to find the temperature gradient.

$$QA_1 - \left[\frac{2kA_2}{L} + \sigma T_{ave}^3 A_3\right]\left(T_1 - T_2\right) - A_4 \sigma T_1{}^4 = 0$$

and

$$\left[\frac{2kA_2}{L} + \sigma T_{ave}^3 A_3\right]\left(T_1 - T_2\right) - A_5 \sigma T_2{}^4 = 0$$

Where Q = solar radiation

A_1 = area of solar radiation

k = thermal conductivity for aluminum

A_2 = wall thickness of tube

T_{ave} = average boom temperature

A_3 = internal radiating area

L = thermal conduction path

A_4 = external radiating area - top half

A_5 = external radiating area - bottom half

The results are:

$$T_1 - T_2 = 22.8^\circ C\ (41^\circ F)$$

To find the deflection of the boom, a linear thermal gradient was assumed across the tube. With a thermal expansion coefficient of $21.6 \times 10^{-6}\ \mathrm{cm}/_{\mathrm{cm}}\ ^\circ\mathrm{C}$ ($12 \times 10^{-6}\ \mathrm{in}/_{\mathrm{in}}\ ^\circ\mathrm{F}$) the maximum stretch of the fibers will be $492 \times 10^{-6}\ \mathrm{cm}/_{\mathrm{cm}}$ ($\mathrm{in}/_{\mathrm{in}}$). Since the boom will curve along a circular arc, the radius of the arc will be:

$$\rho = \frac{\text{dia of boom}}{\text{strain of metal}} = 4.65 \times 10^2 \mathrm{m}\ (1.83 \times 10^4\ \mathrm{in})$$

The deflection of the tip will be:

$$x = \rho - \rho \cos \left(\frac{\text{boom length}}{\rho} \right) = .356\ \mathrm{m}\ (14\ \mathrm{in})$$

This tip deflection is larger than would be expected in the actual boom since many "worst case" conditions have been assumed. A more detailed analysis will be required in accomplishing a detailed design of the boom. If the deflection is thus found to be larger than desired, it can be reduced either by wrapping the boom in a shielding material or by putting holes in the boom so that the "backside" also sees some solar radiation.

An approximate analysis was made to find how long it would take for the boom thermal deflection to "swing" to the opposite side, if the boom was turned 180° with respect to the sun. The temperature varies approximately as:

$$T(t) = T_o + \Delta T\,(1 - e^{-11.5\,t})\left\{T_o + \Delta T\,(1 - e^{-11.5t})\right\}$$

where

T = new temperatures

T_o = old temperature

ΔT = temperature difference between the two halfs at $t=0$

t = time (hrs)

From this equation it can be seen that 50% of the temperature change takes place in .06 hours. 90% of the change takes place in .2 hours or 12 minutes. Since this temperature change and also thermal deflection change takes place in the time required for a typical manipulator task, it is desirable to shield the boom to eliminate the oscillation of $\pm$ .356 m ($\pm$ 14 in).

A simple thermal radiation shield (for example coated Mylar wrapped around the boom) with a radiation transfer coefficient of $\varepsilon = .1$ would substantially reduce the temperatures of the front and back of the boom. For example, using a four mode approximation with radiation and conduction between the two halves of the tube and radiation only between the thermal blanket and the tube, the front and back temperatures were calculated to be: -27.4°C (543.4°R) and -25.1°C (539.2°R). This temperature difference [2.3°C (4.15°F)] would reduce the thermal deflections to $\pm$ 3.6 cm ($\pm$ 1.4 in). Since this amount of deflection is less than deflections caused by typical tip forces, it probably can be ignored, particularly since the thermal time constant with radiation shield would be increased by roughly an order of magnitude (90% change in 120 minutes - see above analysis).

6.3.5 Boom/Root Point Electrical Connectors

The overall root point/end connector assemblies are shown in Figures 2.3-4 and 3.1-3 and they are described in detail in Section 3.1.2. The mechanical aspects of the assemblies appear straightforward, however, space type experience with the electrical connectors portion is very hindered. It is important to note that the electrical connector problem is not unique to the walking boom concept. Any manipulator concept capable of connecting to a variety of electrically actuated end effectors must have such an electrical connector assembly.

The electrical functions which must pass from the boom to the root-point are of three types. There must be two power carrying contacts capable of about 10 amps each, 30 signal carrying wire of about AWG 22 size, and four coaxial cables which transmit the TV video signals. To reduce size, all three functions must be carried through one connector. In order to increase reliability, two identical connectors should be used. The two connectors would be totally wired in parallel to present "OR" gates for current flow, i.e., given that a pin, or pins of one connector was damaged, current would still pass unhindered through its second connector counterpart.

Candidate electrical connectors for this application must be capable of aligning themselves to some extent since insertion of the boom may not be precise enough for "rigid" pins. Any such auto-aligning device will necessarily have a large amount of contact "slop". This slop is totally unacceptable once the connector is completely mated since it will allow contact "chatter" or otherwise not maintain a good, firm signal path. Further, any method employed to clamp the contacts (i.e., remove contact slop) must not be of a type which requires undue force to unmate the connector as the boom walks about.

A second important parameter of the electrical connector is its ability to withstand long-term mating in space. It is quite conceivable that the boom will remain in one root point for several months. Materials must be used such that cold-welding between the male-female contacts cannot occur during these prolonged matings. The effect of this cold welding would at worst permanently anchor the boom to the root point or at least cause excessive pitting (wear) on the contact during disconnect which would quickly shorten the lifespan of the device.

The final important parameter is the ability to mate-disconnect large number of cycles. During the desired ten year life span of the boom, it is not unlikely that a total of 5,000 to 10,000 mating cycles would be required. Thus any candidate connector must meet the first two requirements in such a manner as to subject the electrical contacts to an absolute minimum amount of wear.

This section presents a survey of several state-of-the-art connectors, an examination of their adherence to the above three parameters and the presentation of two candidate connectors.

6.3.5.1 Existing Connectors

MBA has searched available literature, talked with major aerospace contractors and met with several connector manufacturers to determine the state-of-the-art of connectors used on man-space systems.

The AMP Corporation has developed the "G-Series", a modular connector which carries power, signal and coax connectors. This device has been used on the F-111 aircraft and on the Poseidon warhead. This "G-series" is illustrated and fully discussed below. It is sufficient here to mention that this connector meets NASA Specification 40M39569 which requires 500 mating cycles in normal atmosphere and 100 hours of current conduction in 1×10^{-6} mm Hg.

The Deutsch Company produces the high contact density 81511D connector which sets Mil-C-0081511D. This connector has been recommended by North American for use on the Apollo capsule. An earlier version, the LW series, was used extensively on the Lunar module.

The 81511D uses a pin insertion technique as shown in Figure 6.3-12. The female is made from a gold plated beryllium copper and is drilled out and tapered as shown. Thus the male must force open the female which then, due to the inherent spring compression closes around the male and holds it tightly. Withdrawal is accomplished by overcoming the spring force as the male is retracted. The male contact is firmly embeded in its shell while the female is in a pliable (springy) material. This allows some initial mis-alignment of the two parts which is corrected as the male progresses into the female. The advantage of such an arrangement is that a good firm connection is made over a large amount of contact surface area. However, while this connector has been cycled 500 times, no data is available beyond that number.

The Bendix Corporation has completed development on a "Zero G Connector". This device is shown in Figure 6.3-13. The male end is placed in the female shell then the connection is electrically made by tripping the lever shown in the figure. The Zero G Connector is space rated and has been used by astronauts on the Lunar Rover module.

Matrix Sciences makes a connector which is a variation of the 81511D. The pin arrangement is shown in Figure 6.3-14. The female uses a pair of spring wiper contacts which contract to allow the male to enter, then expand to hold the connection firm. This device has been used on the Lunar Rover and the Minuteman warhead separation cable. It meets NASA Spec. 40M39569.

6.3.5.2 Deficiencies of Existing Connectors

Except the Bendix Zero G, all the connectors discussed above are space rated (the Bendix is presently being qualified). To meet NASA 40M 39569 a connector need only be cycled 500 times and conduct current for 100 hours in 1×10^{-6} mm Hg. While this spec has proven very satisfactory in past applications, it does very little for the present use. NASA 40M 39569 does not address itself to thousands of mating cycles, long term vacuum exposure, and long term mating as described in the introduction

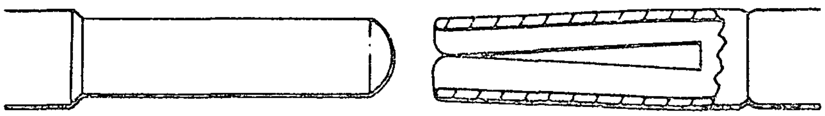


FIGURE 6.3-12.
DEUTSCH COMPANY 81511D CONNECTOR

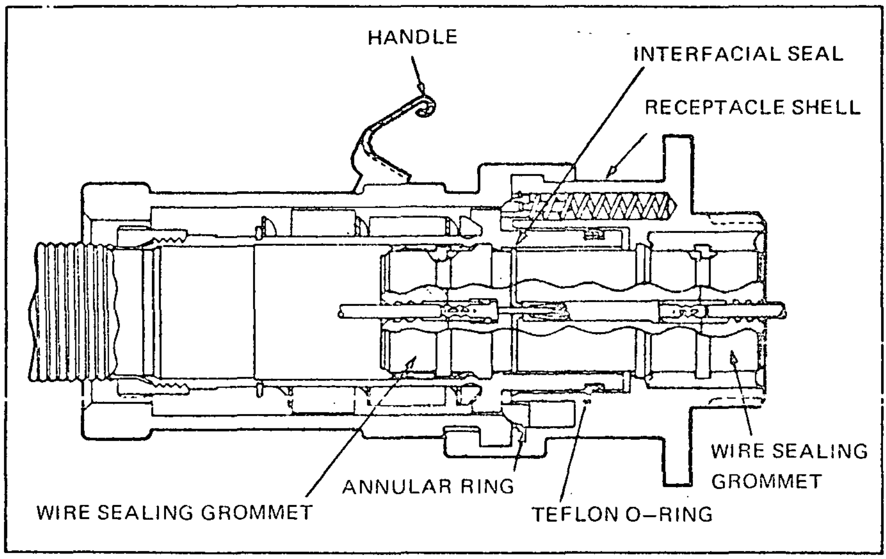


FIGURE 6.3-13.
BENDIX CORP. "ZERO G" CONNECTOR

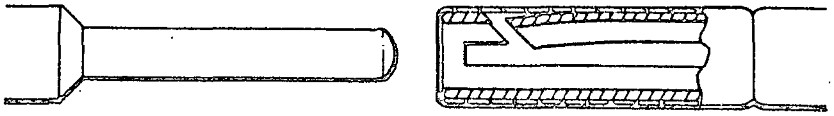


FIGURE 6.3-14.
MATRIX SCIENCE PIN TYPE CONNECTOR

to this section. It appears that the state-of-the-art has not addressed the present application and thus there is no off-the-shelf connectors to meet the present requirements.

6.3.5.3 Candidate Connectors

The shuttle application should present little difficulty in achieving a satisfactory connector since it can be serviced on each return trip. Two approaches can be used to attain the required operational life capability for the space station:

(1) Develop a long life unit capable of operating in space for say ten years, or

(2) Develop a connector with a life capability such that the boom and root point connectors can be replaced (re-cycled) as a part of the normal planned shuttle/space station logistics/maintenance program. The walking boom concept lends itself ideally to the latter approach. The proper approach requires more detailed economic study, however, it is anticipated that the latter periodic maintenance cycle will be preferred. For this case, existing connector technology may very well be adequate for the space station application.

The AMP-G connector series, shown in Figure 6.3-15 appears to be an attractive candidate.

As stated above, it is not known how this connector functions in long duration space exposure, but its construction features make it attractive for remote connect-disconnect operations.

It can be seen from Figure 6.3-15 that the contact arrangement has the three required functions which are "built-up" in modular form to produce one connector arrangement. Discussions with factory representatives determined that the proper wire size and numbers can be fabricated.

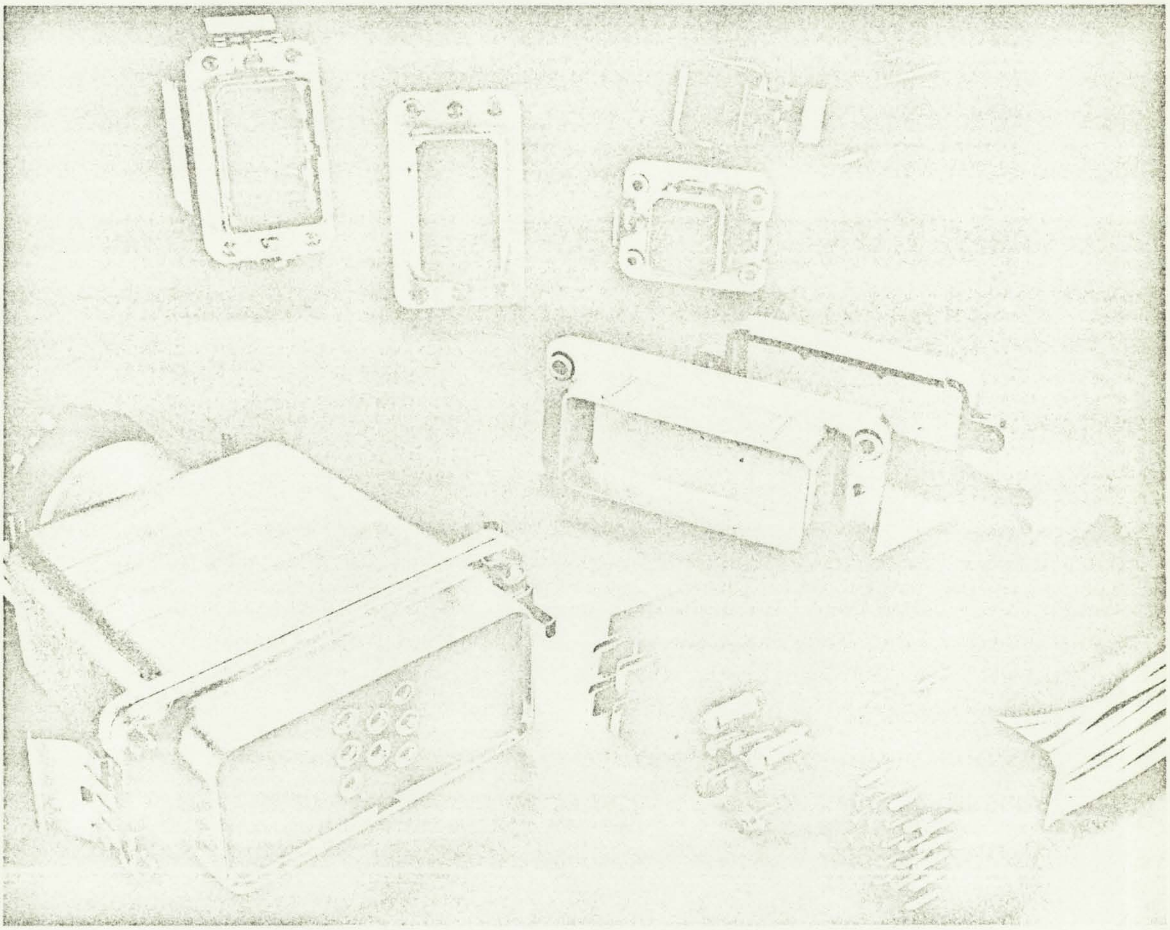


FIGURE 6.3-15.
AMP SERIES "G" CONNECTOR

FIGURE 6.3-16.
DEUTSCH COMPANY FLOATING PLATE CONTACT
CONNECTOR PIN ASSEMBLY

The most attractive feature of this connector is its auto-alignment capability. As can be seen in the photo, the extended metal shell protects the contacts and causes the initial alignment of the connector. As the male shell slides into the female shell, rough alignment is obtained so that the contacts meet within about .025 inches. The material in which the females are embedded is pliable enough to accept a .025 inch misalignment which is corrected as the male enters the female. When the male is fully inserted, a good straight, tight connection is made and the tabs on the male shell catch on the female shell. To release the connection, the tabs are lifted and the male backed out. A sample of this connector was obtained and examined for auto-alignment. Even with intentional gross misalignment, the connection was always made quickly and cleanly.

This connector is rated to only 500 mate cycles. However, the sample examined was a two-year-old demonstrator which AMP feels has been through about 1,000 connections.

The Deutsch Company has developed an interesting connector known as the Floating-Plate Contact. This scheme is shown in Figure 6.3-16. A tapered slot is machined in the side of the socket to allow a leaf spring, loaded plate to seat against and protrude through the bottom of the slot. As the pin enters the socket the plate deflects the spring such that the plate rocks up and over the end of the pin. The leaf spring provides positive side load contact when the pin is fully inserted.

The Deutsch Company has documented 5,000 connect-disconnect normal atmospheric cycles on this scheme and they have tested it close to 10^6 cycles.

The effects of repeated hand vacuum mating on the above type connectors must be established to determine if they are acceptable for the manipulator boom. If they are not, a non-sliding type of contact connector can be devised as illustrated in Figure 6.3-17. As in the reference connector design, the mail pins are placed in the root point to provide protection

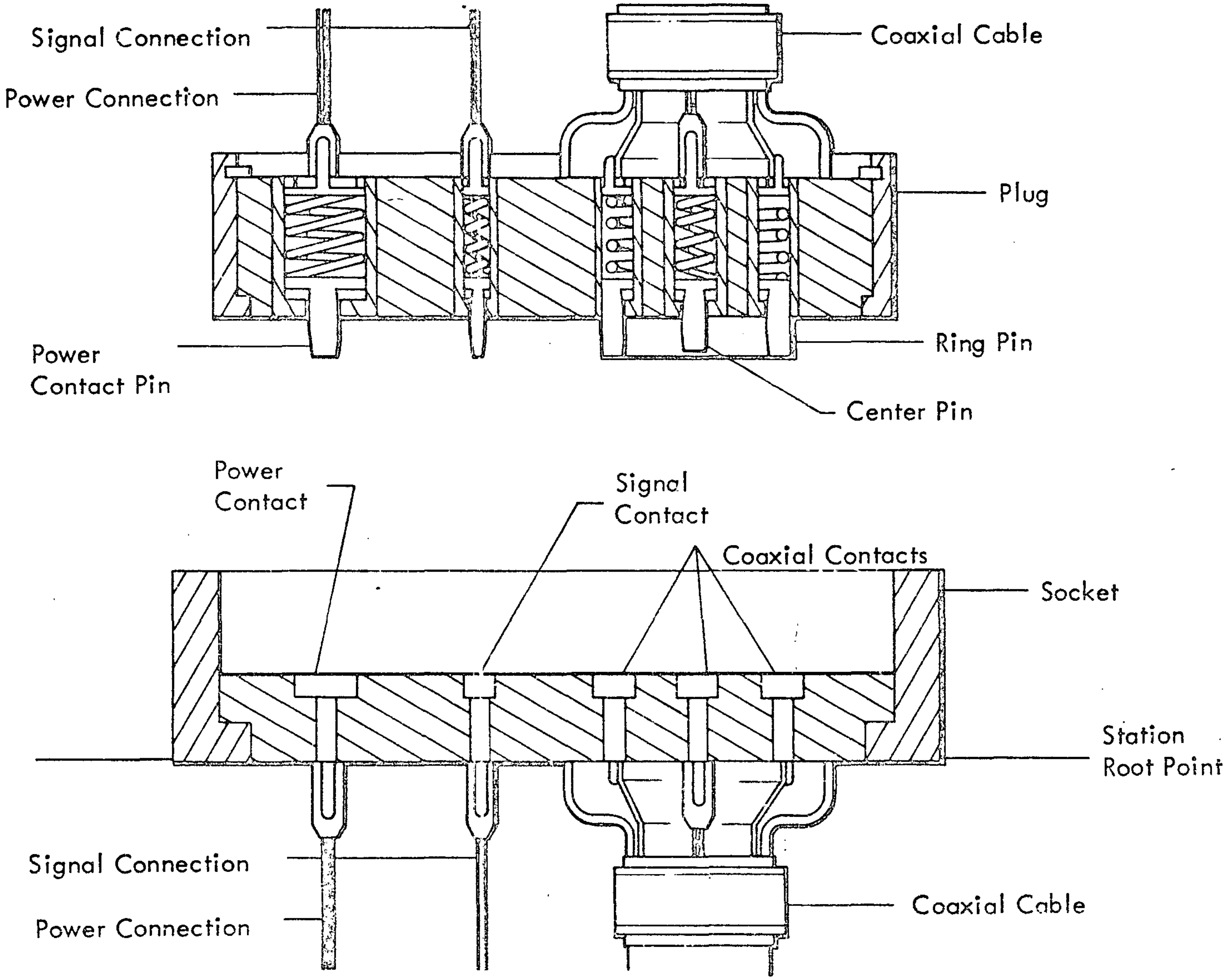


FIGURE 6.3-17
BUTTON CONTACT BOOM ELECTRICAL CONNECTOR SCHEMATIC

against damage. The female contacts located in the end connector are spring load "buttons" which are pushed back into their sockets by the male pins as the connector is mated. The buttons are free to "tilt" to assure a flat face-to-face contact. This configuration would also have a relatively large axial misalignment capability.

6.4 Man/Machine Interface Analysis and Design

6.4.1 General

This section develops the physical design of the manipulator control console, including layout of the displays and controls, and sizing for efficacious use by the anticipated operator population.

6.4.2 Display and Control Definition

Analysis of the recommended control concept and the detailed interface requirements permits definition of the specific displays and controls the operator must have to accomplish his control tasks. These are listed by name and function in Tables B and C. Included in these tables is an indication of control regimen to which the component belongs, and whether it is of primary, secondary, or auxiliary importance.

6.4.3 Functional Analysis

The primary criteria for optimum functional design of the operator's console are:

(1) Displays and controls which are functionally related should be grouped together.

(2) Displays and controls which are most important should be placed where they are easiest to see and reach.

(3) Panel placement and configuration should meet the space requirements of the shuttle crew compartment since room there is more restricted than on the space station, and direct vision is a significant factor.

6.4.4 Operator Station

Figure 6.4-1 shows the work volume allocated to the manipulator operator in the aft section of the 040A shuttle crew station. The operator occupies the starboard half of the aft section, and looks into the shuttle cargo bay through a large glassed area.

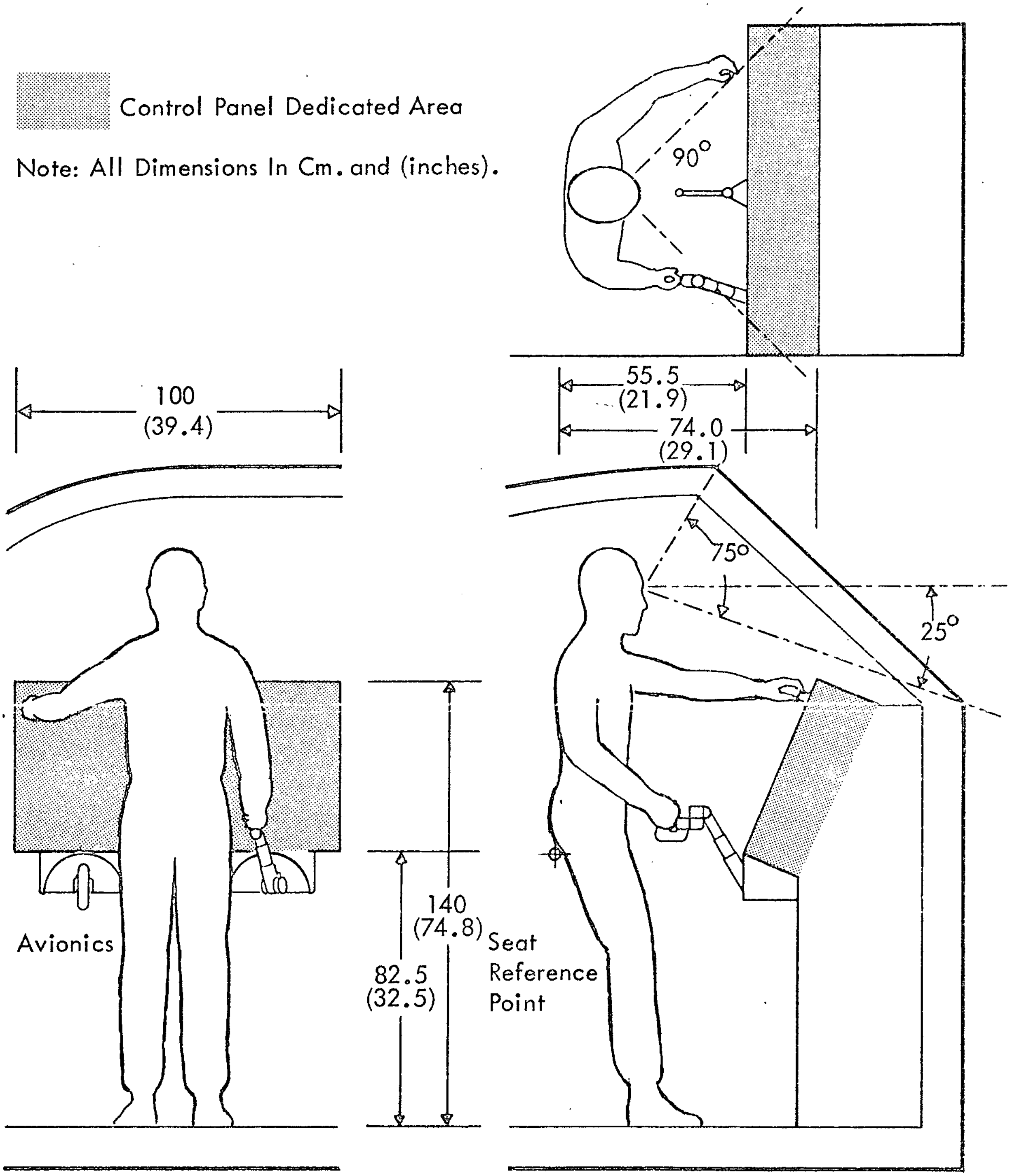


FIGURE 6.4-1

MASTER CONTROLLER USED FOR DEXTEROUS END EFFECTOR CONTROL

Next to him on the right is the aft spacecraft operator's station, and on his left, between him and the shuttle skin, is a space reserved for avionics.

Accordingly, the manipulator control panel must occupy the region directly ahead of the operator, without interfering with his forward vision. Figure 6.4-1 shows a panel of approximately 0.5 square meters (5 square feet) located at this site, within optimum reach of the anticipated user population.

Figure 6.4-2 shows the relationship of the controllers to the control panel. The two master controllers swing down and push into console for stowage, and to provide additional room for the model controller.

The model controller is centrally located, and swings out from its stowed position under the panel when in use. Shuttle or space station coordinates for the model are created by a series of calibrated and "tinker-toy" modular elements which define such real objects as cargo, docking parts, obstacles, etc.

6.4.5 Panel Design

Application of the design criteria listed in Section 6.4.3 to the information of Tables 6.4-1 and 6.4-2 yield two panel layouts. These are diagrammed in Figure 6.4-3. These differ mainly in whether the secondary displays (Overview TV's) are located along a vertical or horizontal visual axis from the primary display. The "horizontal" arrangement has two main advantages, these are:

(1) The visual field is larger horizontally than vertically (about 100° vs 60°). Thus secondary information can be assimilated with less distracting head and eye movement, and at closer range.

(2) More efficient use is made of panel space.

There were no significant advantages of the vertical arrangement. Accordingly, the horizontal design was selected for further development.

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

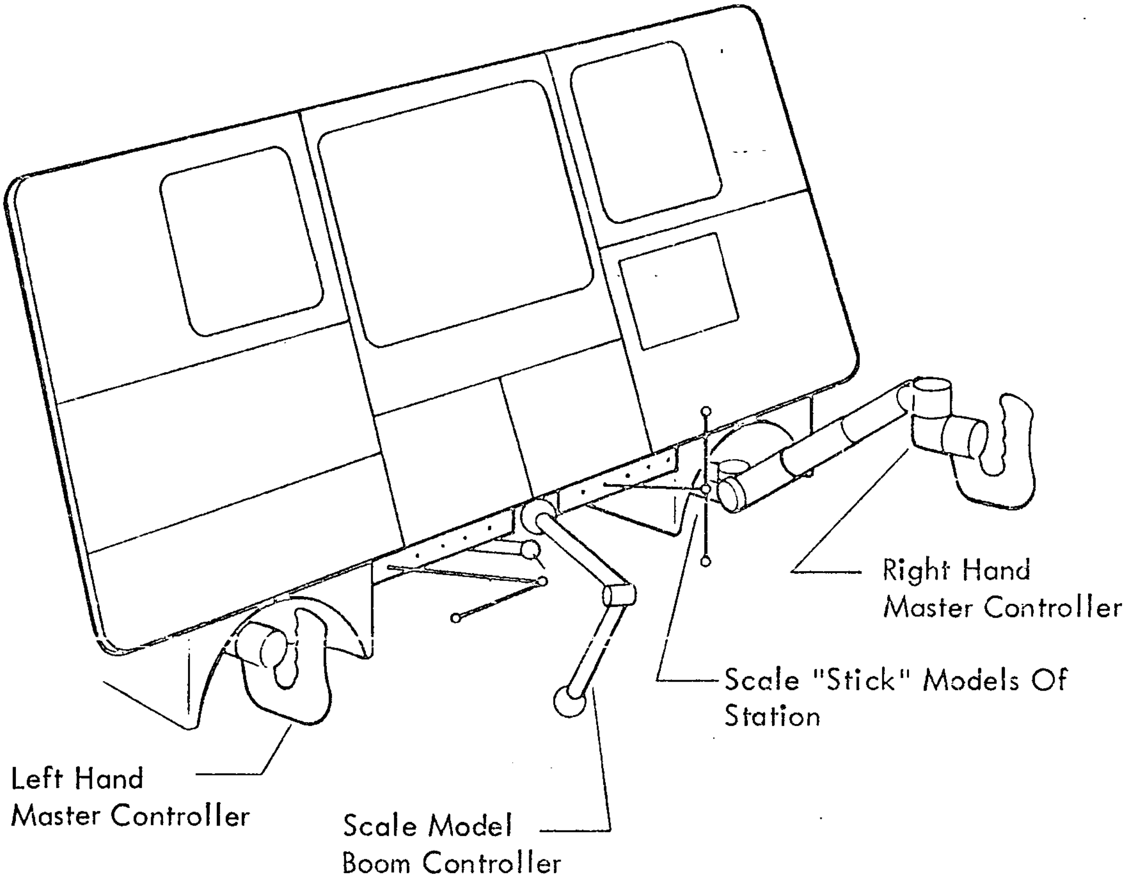


FIGURE 6.4-2
LAYOUT OF MANIPULATOR CONTROLLERS

#	NAME	FUNCTION	MODE (1)				(*)
			T	D	M	E	
D1	Stereo/Foveal TV	Shows Workspace Of Dextrous Manipulators			X		P
D2	Mating & Berthing TV	Shows Distance And Alignment In M&B Operations		X			P
D3	Overview TV-1	Shows View From Camera Boom Or Base Of Main Boom	X			X	S
D4	Overview TV-2	Shows View From Camera Boom Or Base Of Main Boom	X			X	S
D5	Camera-On-Screen	Shows From Which Camera & Display Emanates	X			X	S
D6	Camera Boom Position	Identifies Current Configuration Of Camera Boom	X			X	A
D7	Manipulator Position	Identifies Current Configuration Of Main Boom	X	X		X	P
D8	Effector Status	Indicates Mating And Release		X		X	P
D9	Electrical Systems	Shows Electrical Parameters Of Actuator System				X	A
D10	Computer Input	Verifies Alpha-Numeric Input To Computer	X				A
D11	Computer Output	Presents Data And Messages	X				A
D12	Index Reference	Presents Station Configuration And Indexing	X				A
D13	Program Reference	Presents Programming And Data Input Procedures	X				A
D14	Audio	Inter-Crew Audio Communication	X	X	X	X	S
D15	System Status	On/Hold/Off-For Total Manipulator System	X	X	X	X	P

(1) Translation, Berthing, Manipulation, Emergency

(*) Primary, Secondary, Auxiliary

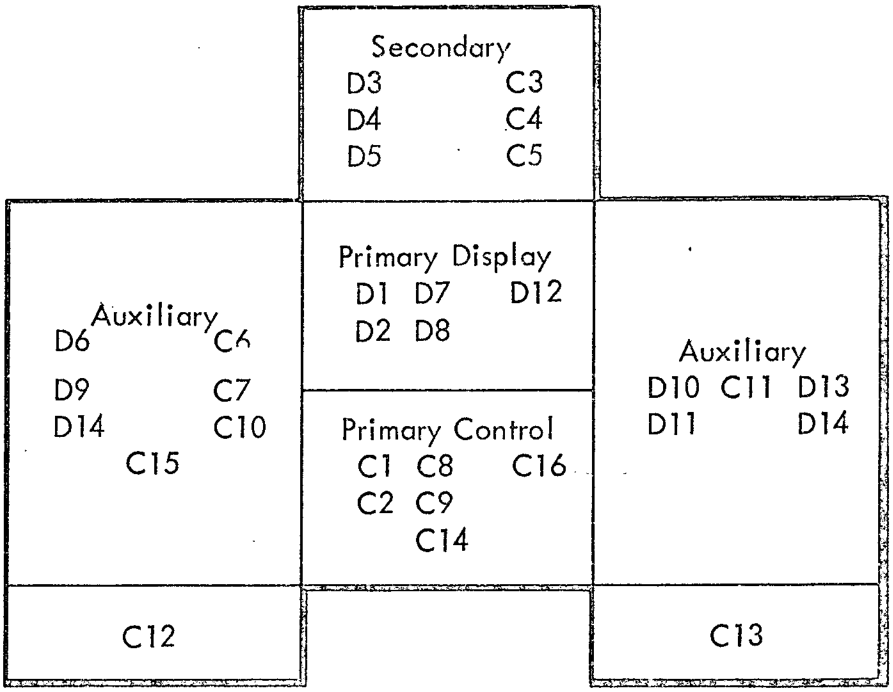
TABLE 6.4-2
CONSOLE DISPLAYS

#	NAME	FUNCTION	MODE[1]				(*)
			T	B	M	E	
C1	Stereo/Foveal Adj.	Adjusts Stereo/Foveal Tv Display			X		P
C2	Mating & Berthing Adj.	Adjusts Mating & Berthing TV Display		X			P
C3	Overview TV-1 Adj.	Adjusts Overview TV Display #1	X			X	S
C4	Overview TV-2 Adj.	Adjusts Overview TV Display #2	X			X	S
C5	Camera Select	Assigns Cameras To Displays	X	X		X	S
C6	Camera Boom	Positions Camera Boom	X	X		X	A
C7	Lighting	Adjusts Lighting For Boom Cameras	X	X		X	A
C8	Manipulator Boom	Controls Individual Actuators Of Manipulator Boom				X	P
C9	Effector Release	Releases End-Effector From Module, Station, Etc.	X	X			P
C10	Power Adj.	Performs Necessary Adjustments To Actuator Power				X	A
C11	Computer Input	Inserts Alpha-Numeric Data to Computer	X				A
C12	Left Controller	Controls Left Dextrous End Effector			X		A
C13	Right Controller	Ctrls Boom End Point & Cluster & R Dextrous End Effector			X		A
C14	Model Controller	Develops Boom Trajectories for Computer	X				A
C15	Audio Select/Adj.	Sets Up Inter-Crew Communications Link	X	X	X	X	S
C16	System Status	Puts Manipulator System In On/Hold/Off Status	X	X	X	X	P

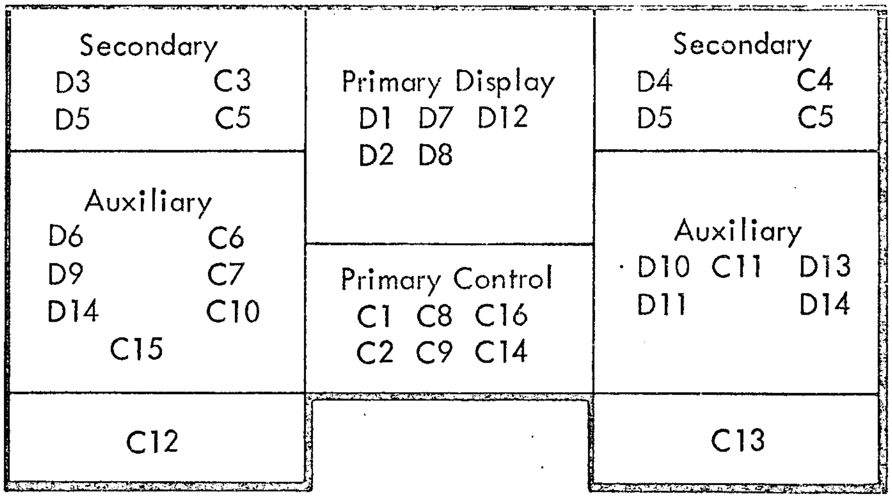
(1) Translation, Berthing, Manipulation, Emergency

(*) Primary, Secondary, Auxiliary

TABLE 6.4-1
CONSOLE CONTROLS



a. Vertical Configuration



b. Horizontal Configuration

FIGURE 6.4-3
ALTERNATE CONSOLE LAYOUTS TO OPTIMIZE
DISPLAY/CONTROL LOCATION

Figure 6.4-4 shows the console design concept based on the selected configuration, and identifies the major console components. Displays and controls are related by function, and those required for specific operating modes are located in contiguous areas. This is demonstrated by Figures 6.4-5 through 6.4-8, which identify the primary console areas for each control mode. Emergency operation, which is a "fall-back" situation, requires the greatest proportion of panel capability, because its needs cannot be rigorously defined. Camera, lighting, and audio set-up are considered secondary console areas for all operations. The following paragraphs describe in brief the main man/machine design factors in each component section:

(1) Central TV

A central TV screen is shared by the Stereo system and the Mating and Berthing display. This is feasible because the displays are not used simultaneously, and involve separate, switchable, cameras. Adjustment controls are located directly below and are separated by viewing mode. Those for Mating and Berthing are the standard TV controls, those on the right included specialized Stereo convergence, sync, etc.

(2) Overview TV's

Smaller monitors are provided for the overview function. Associated with each is a camera-select switch and a standard set of video adjustments. Which display is used for which camera will depend on the task at hand.

(3) Computer Communications (Figure 6.4-9)

An alpha-numeric CRT displays input data for verification and also output in the form of numbers and messages. Anticipated requirements are less than 30 lines at 70 characters/line. This is well within current equipment capabilities.

A solid-state keyboard is used to enter index values, request computer functions, etc. It is anticipated that the keyboard will be predominantly special-purpose keys, and that basic programming, if it occurs,

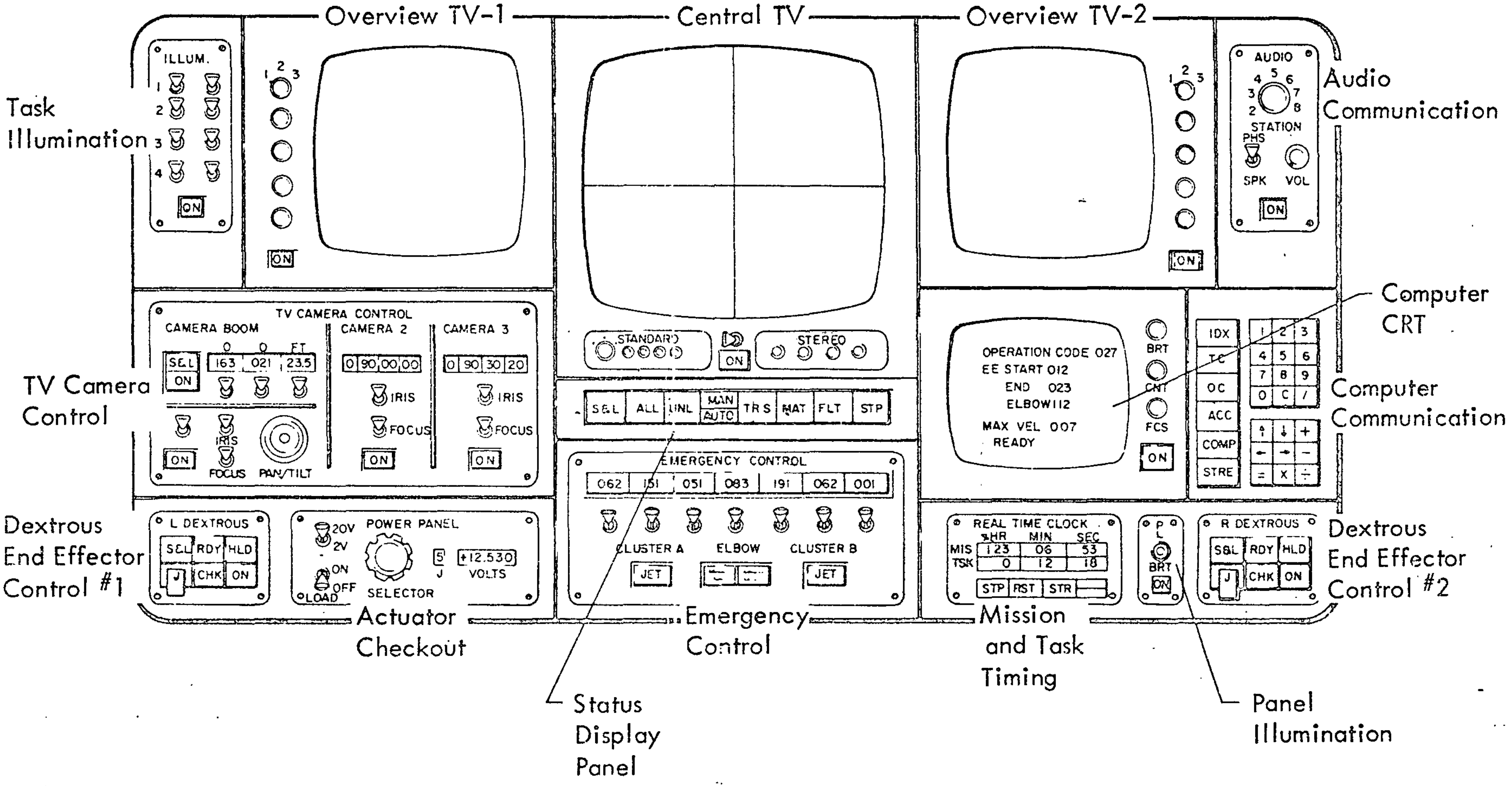
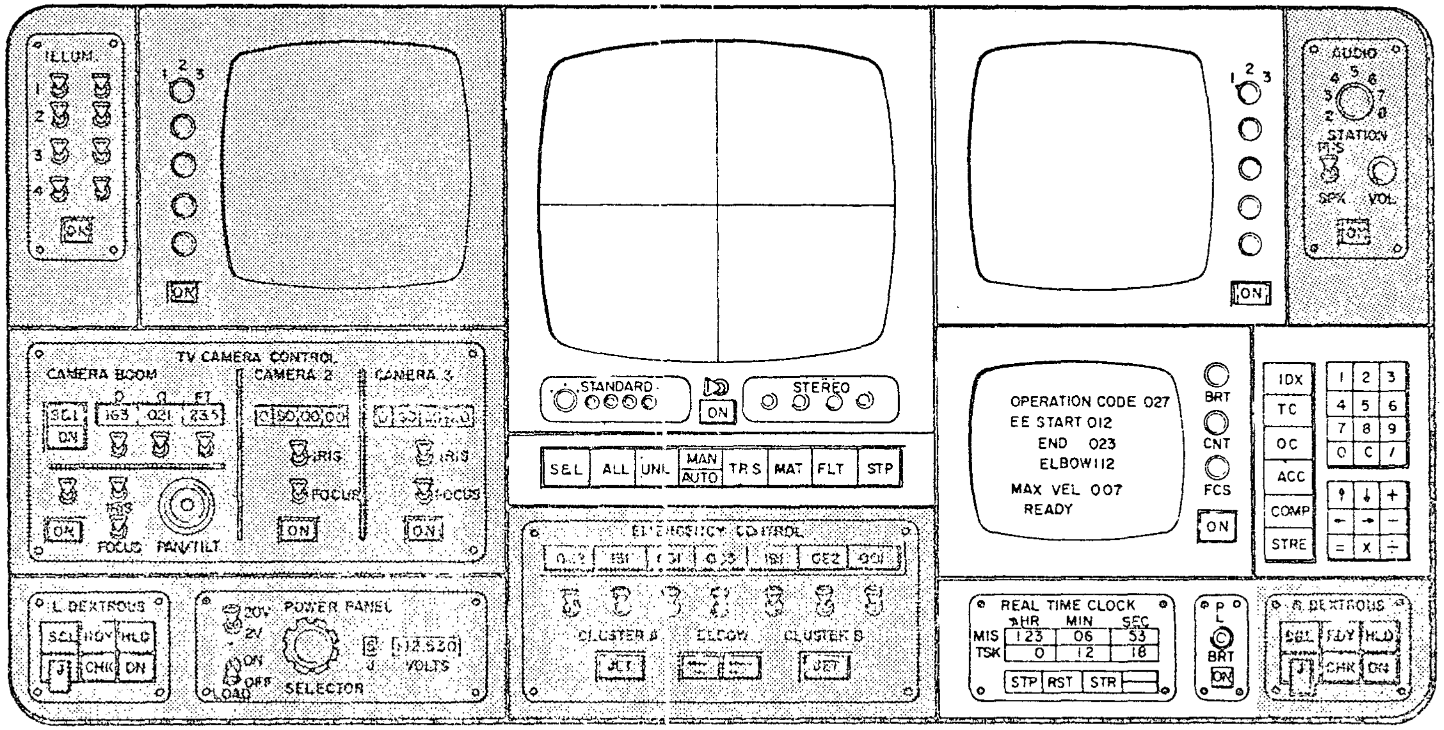
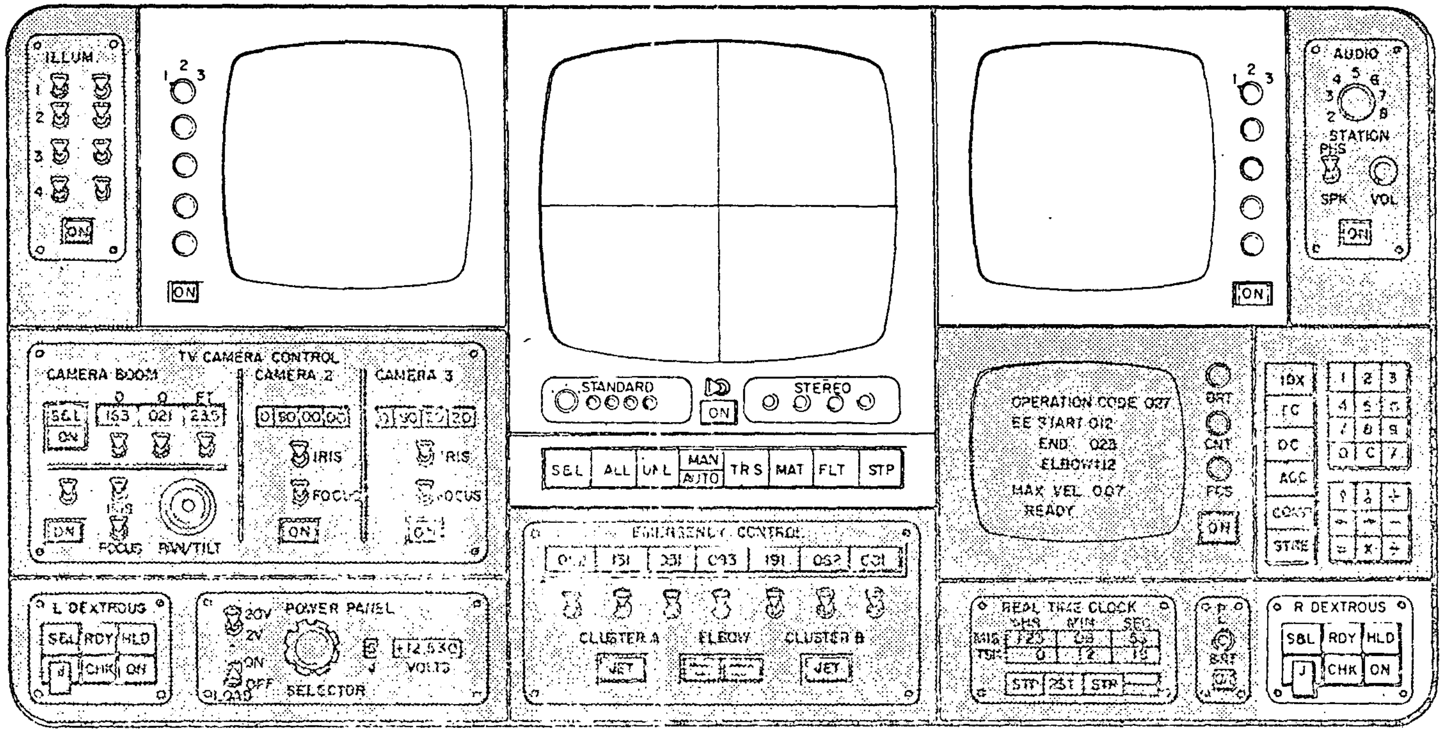


FIGURE 6.4-4
MANIPULATOR CONTROL PANEL LAYOUT



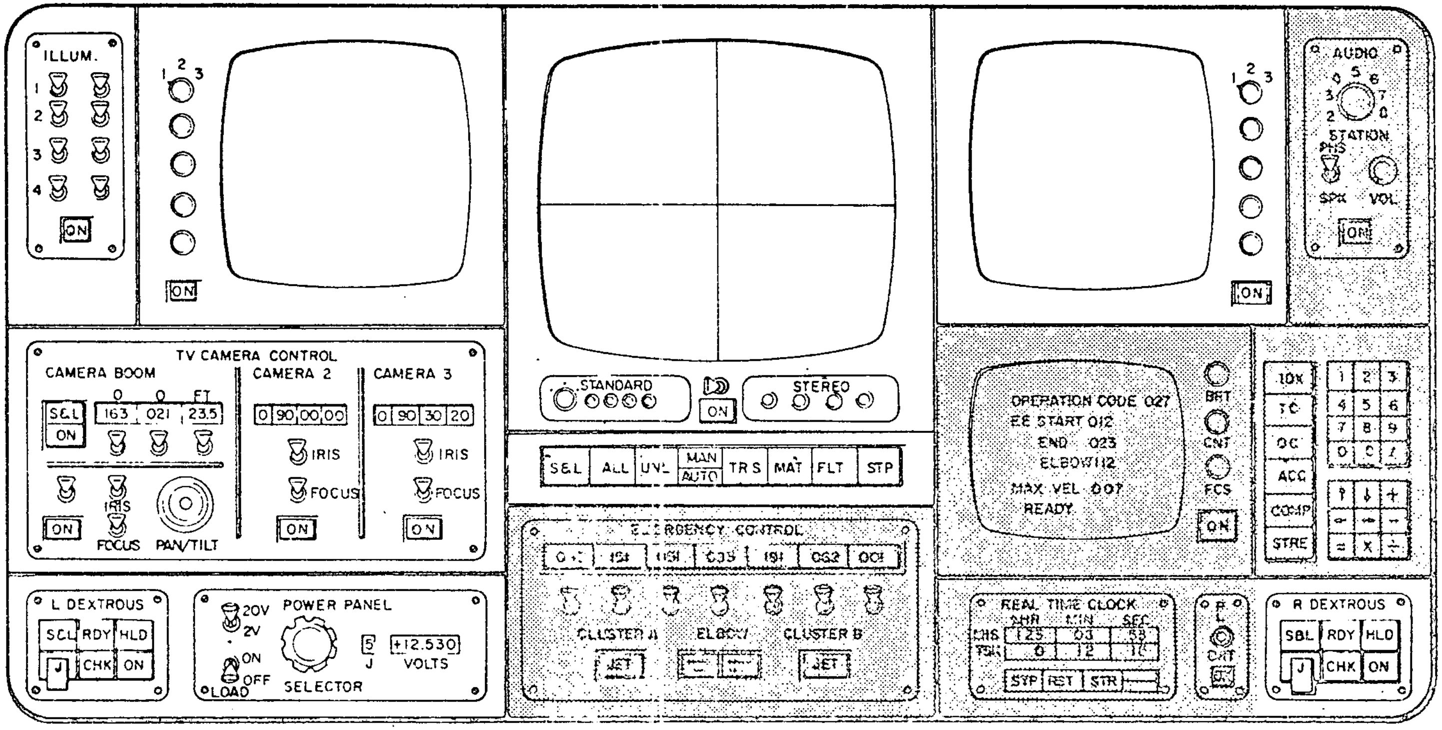
(Shaded Area Non-Primary)

FIGURE 6.4-5
PRIMARY PANEL AREAS USED IN TRANSLATION CONTROL



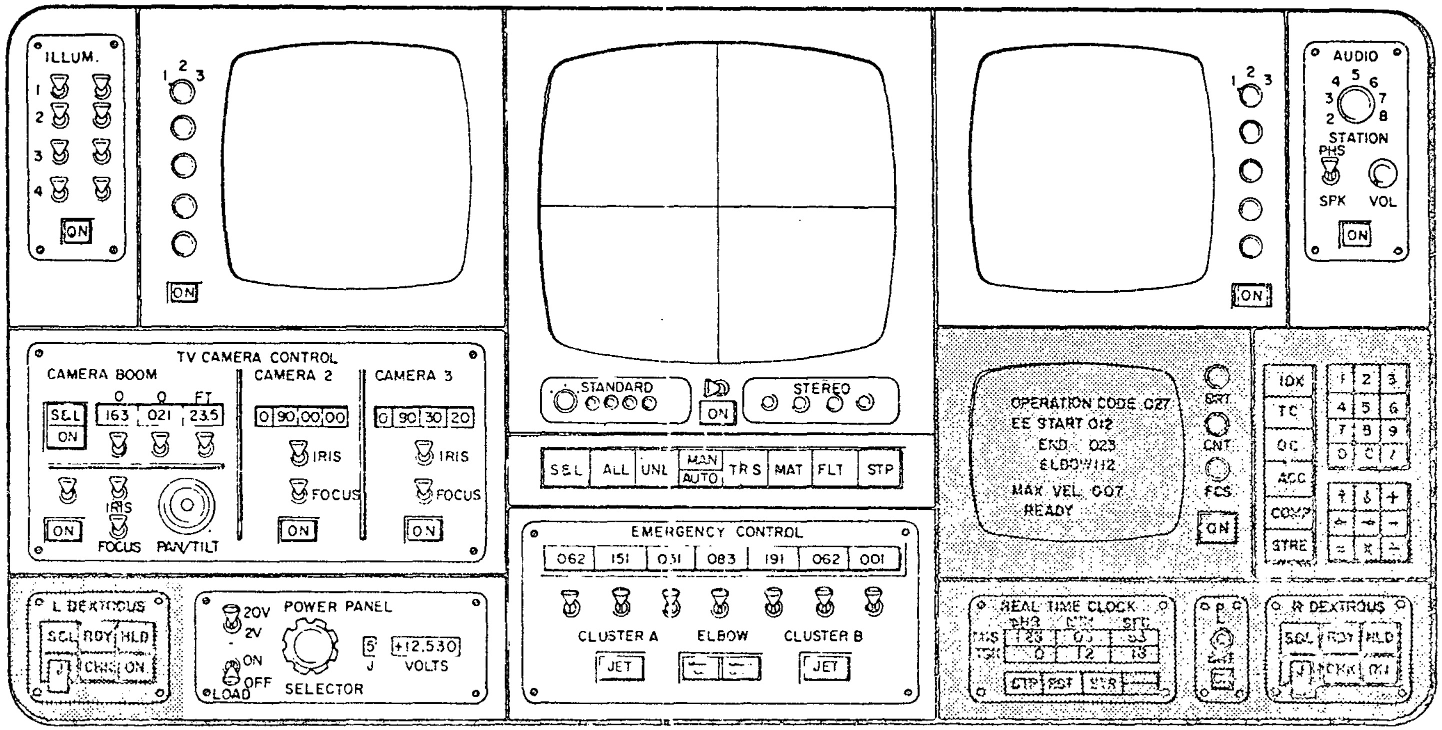
(Shaded Area Non-Primary)

FIGURE 6-4-6
PRIMARY PANEL AREAS USED IN MATING AND DOCKING CONTROL



(Shaded Area Non-Primary)

FIGURE 6-4-7
PRIMARY PANEL AREAS USED IN DEXTROUS CONTROL



(Shaded Area Non-Primary)

FIGURE 6.4-8
PRIMARY PANEL AREAS USED IN EMERGENCY CONTROL

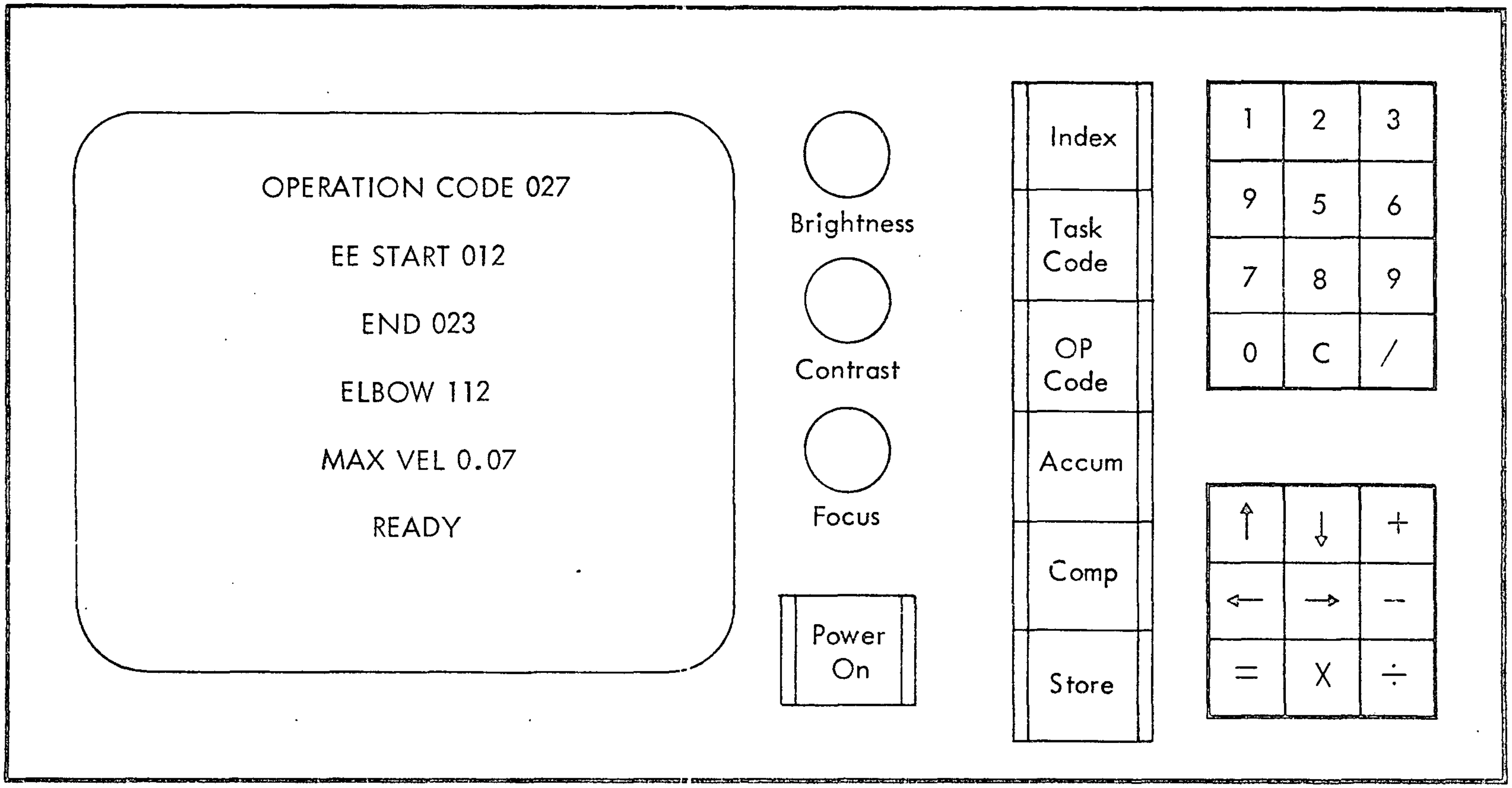


FIGURE 6.4-9
PRELIMINARY DESIGN COMPUTER COMMUNICATIONS PANEL

will be carried out at another location. The functions shown in Figure 6.4-9 are tentative; final selection will depend on detail design of the supervisory language.

(4) Real-Time Clock (Figure 6.4-10)

Mission time and task time are provided on a miniature digital display.[1] Control buttons provide for task time settings through the computer communications panel numerical keyboard.

Localized adjacent to the Real-Time Clock is the Power ON/OFF and Brightness Adjust for the panel illumination.

(5) Status (Figure 6.4-11)

A centrally located panel contains lighted pushbuttons which display and control the critical sequence of boom activation, hold, effector release, effector mating, etc. Included is a "panic stop button" which freezes boom operations in any mode.

(6) Emergency Control (Figure 6.4-11)

Emergency control is closely associated to boom status. A set of seven switches drive the separate boom actuators in "extension" and "retraction" at a fixed slow rate. Digital displays for each driven joint show the joint position with respect to its index point. Jettisoning of either end cluster is controlled from the emergency panel.

(7) Power (Figure 6.4-12)

Power checkout of the various actuators is performed at the power panel. The panel is normally connected to the main boom. When the dextrous end effectors are in use, the panel can be swtiched to their activators by pushing the CHK button on the corresponding effector panel.

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[1] For this and the other small digital readouts on the panel, liquid crystal techniques offer a sharp, bright, and low-power display.

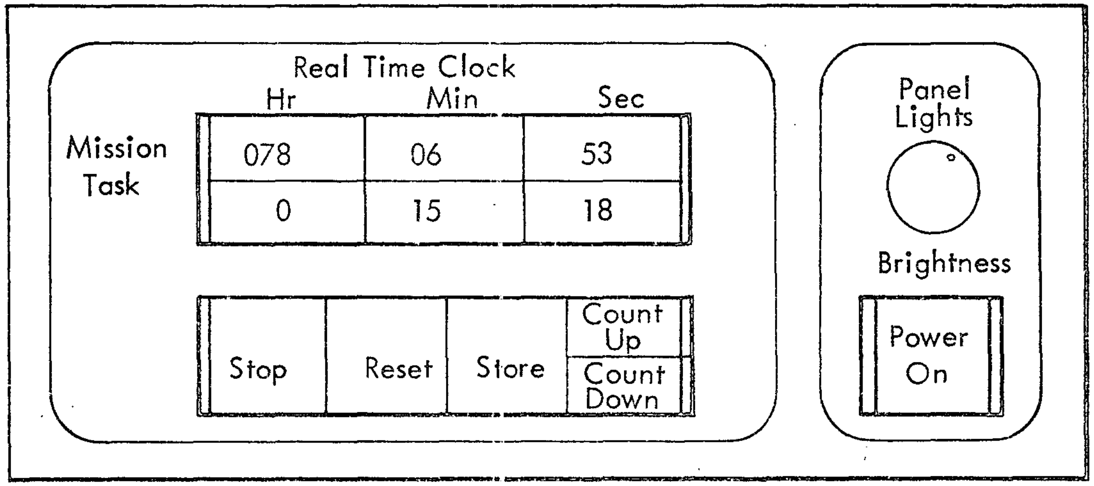

FIGURE 6.4-10
CLOCK AND LIGHTS PANEL

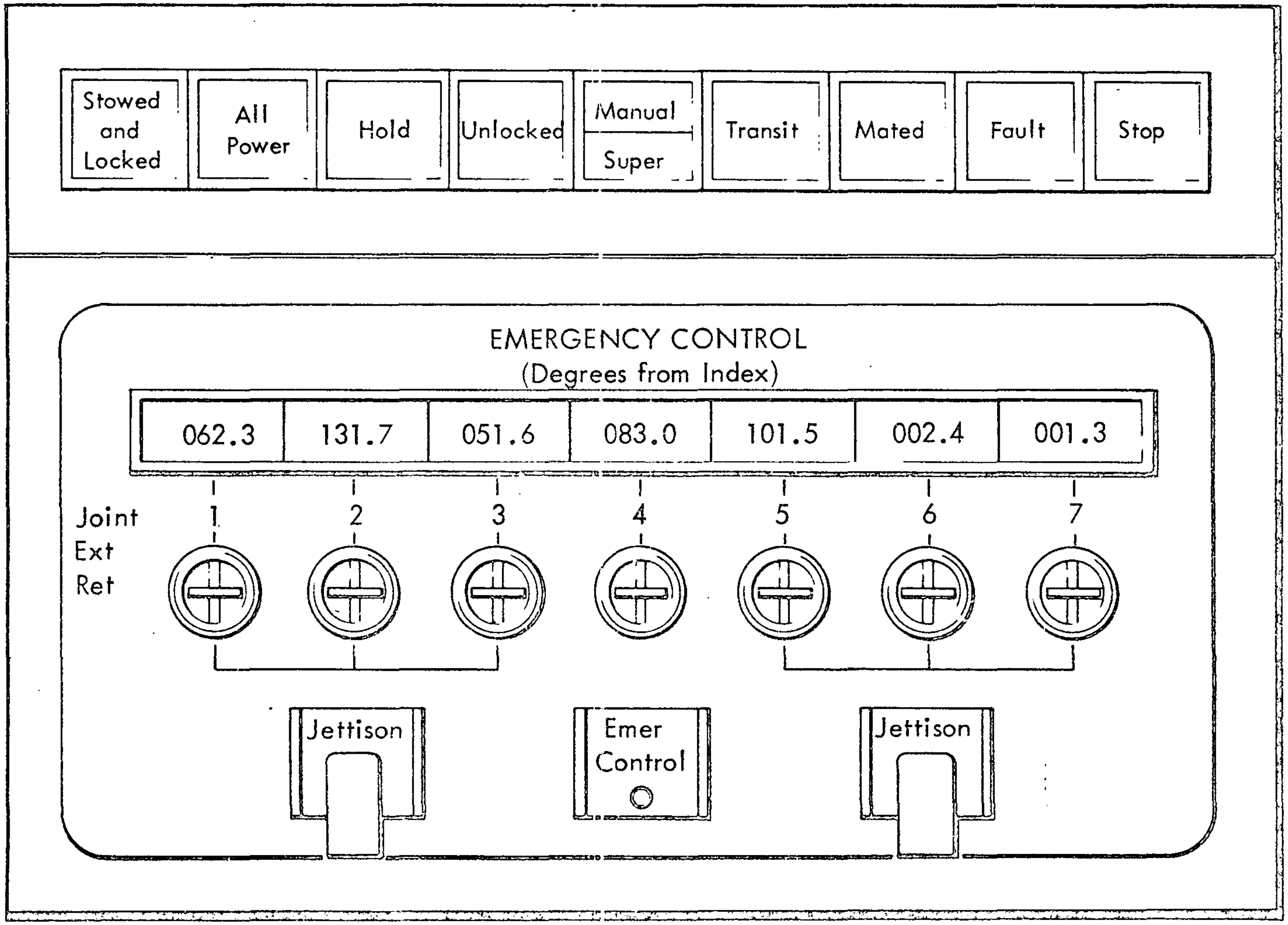

FIGURE 6.4-11
SYSTEM STATUS AND EMERGENCY CONTROL PANEL

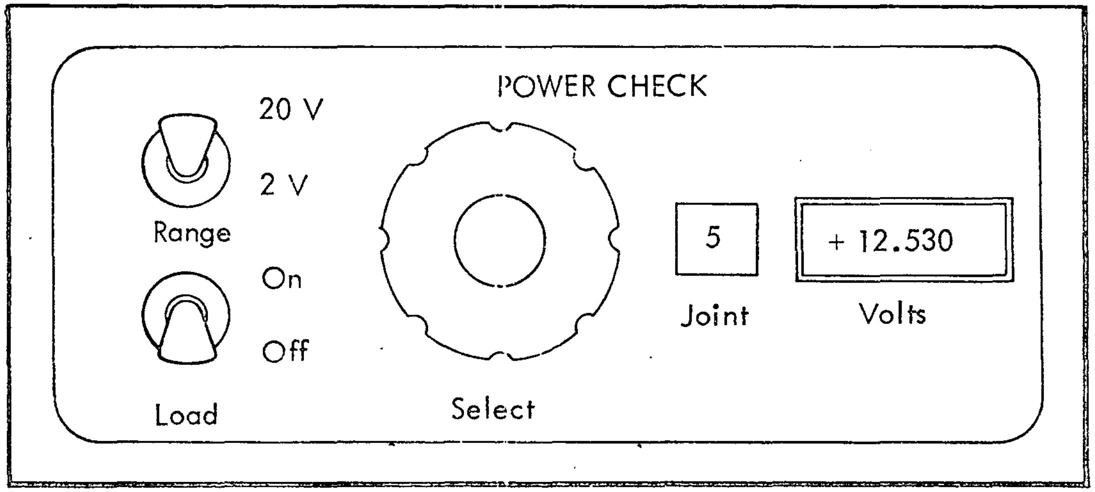

FIGURE 6.4-12
POWER CHECKOUT PANEL

(8) Camera Control (Figure 6.4-13)

Provision is made for deploying the camera boom and orienting the camera. Cameras 1 and 2 at either end of the main boom are oriented to index positions only. This and focus are provided for all cameras; zoom control is provided for the isolated unit.

(9) Illumination and Audio (Figure 6.4-14)

Lighting sources are utilized to heighten TV contrast and soften and emphasize space shadows. Control of the several available sources is on an "Off", "Half-Power" or "Full-Power" basis.

The manipulator operator maintains audio communication with other members of the flight and mission team. The audio control panel allows him to select his audio source, and adjust volume as well as listening means.

(10) Master Controllers (Figure 6.4-15)

Individual status panels are provided for the left and right master controllers. Progression to the "Ready" status switches the master controller signals from the main boom to the dexterous "arms" or other end effector as required.

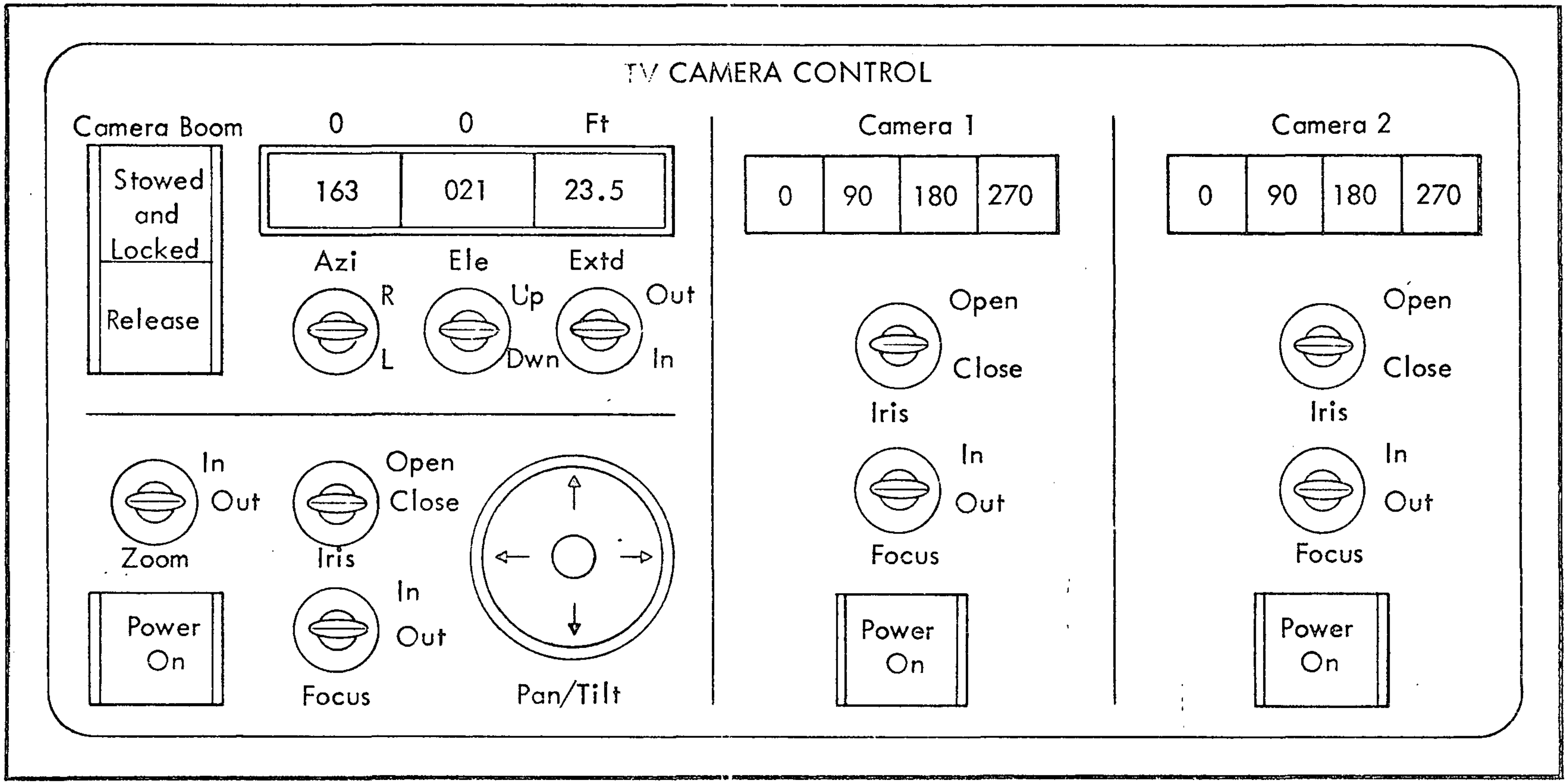

FIGURE 6.4-13
TV CAMERA CONTROL

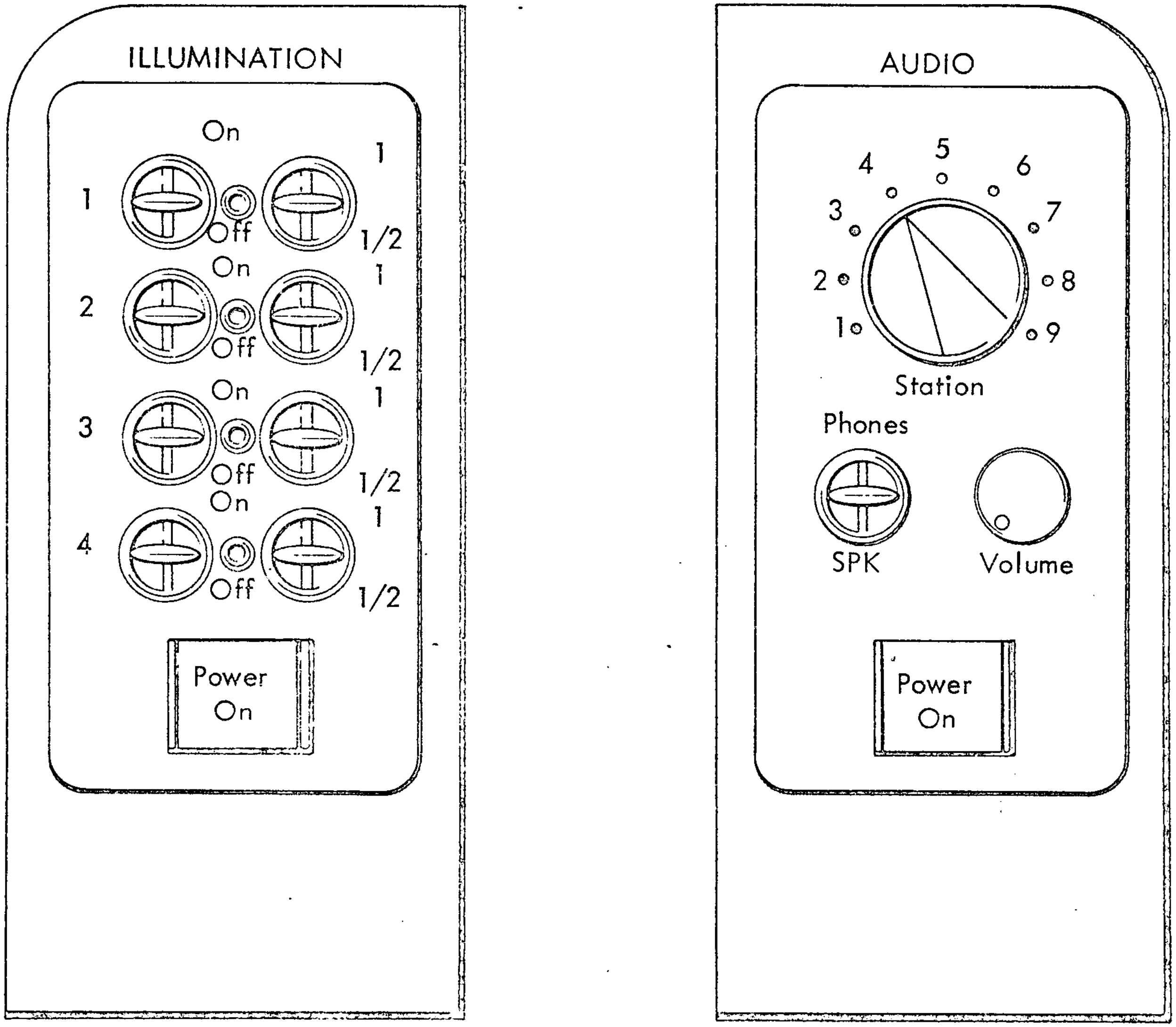

FIGURE 6.4-14
ILLUMINATION AND AUDIO PANELS

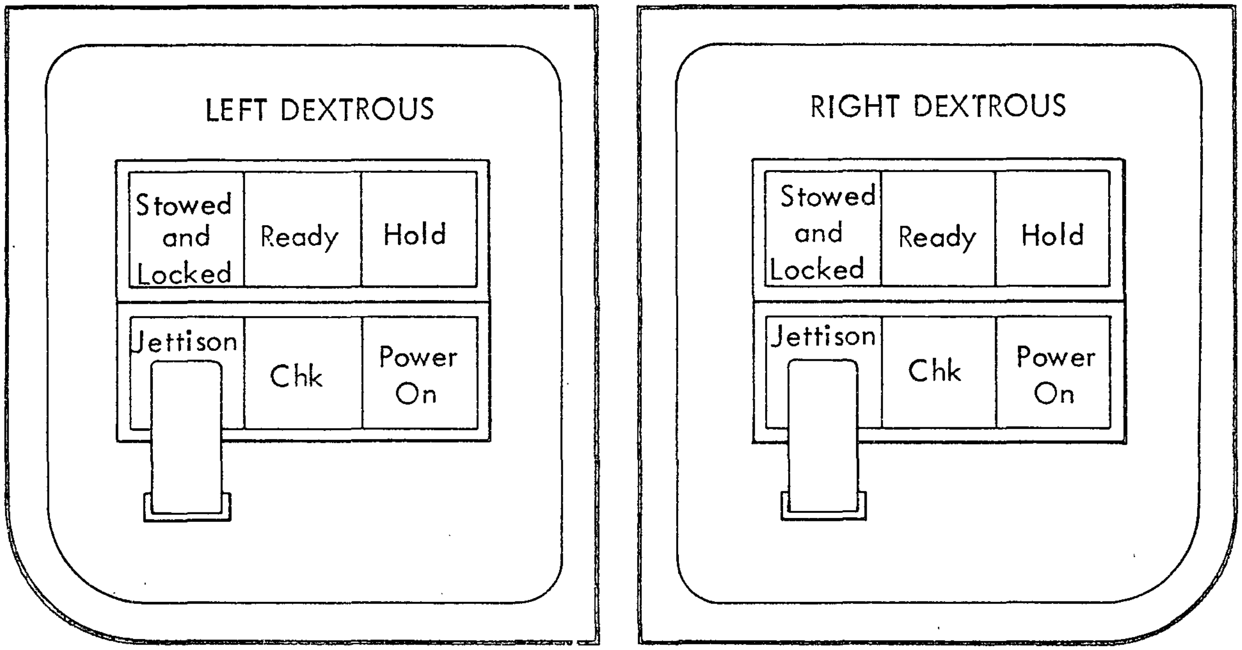

FIGURE 6.4-15
DEXTROUS END EFFECTOR CONTROLLER STATUS

6.4.6 Controllers

The master controllers and boom scale model controller are illustrated in Figure 6.4-2. The computer software program used with these controllers for the various control modes are described in Section 6.6 "Boom Control System Analysis and Design". Simulation studies accomplished on this program of a small scale model computer controller system are described in Volume IV, "Simulation Studies".

The master controllers can be used in three modes:

(1) Dexterous end effector position-position, bilateral force reflecting control;

(2) Main boom end point force to rate control with force reflecting position-position wrist control; and

(3) Main boom wrist position-position force reflecting control when the boom is under computer supervisory control.

The master controller shown in Figure 6.4-2 has 7 DOF's. The shoulder slides in and out (1); the shoulder has vertical axis swing (2); and horizontal axis pivot (3); the wrist has horizontal axis pivot (4); vertical axis swing (5); and wrist roll (6). In addition the arm connecting the shoulder and wrist telescopes for the 7th DOF. With this kinematic configuration, the hand grip can be moved throughout the working envelope as shown in Figure 6.4-16 without requiring "flipping over of the elbow" or large movements of the controller links as might be required with a more conventional 6 DOF fixed shoulder, elbow type controller.

For dexterous 2 arm end effector control, both left and right controllers are used. (The master controllers are transferred to the end effectors pushing the main boom "hold" and the dexterous panel "ready" buttons). The controller joint positions are fed into the computer which

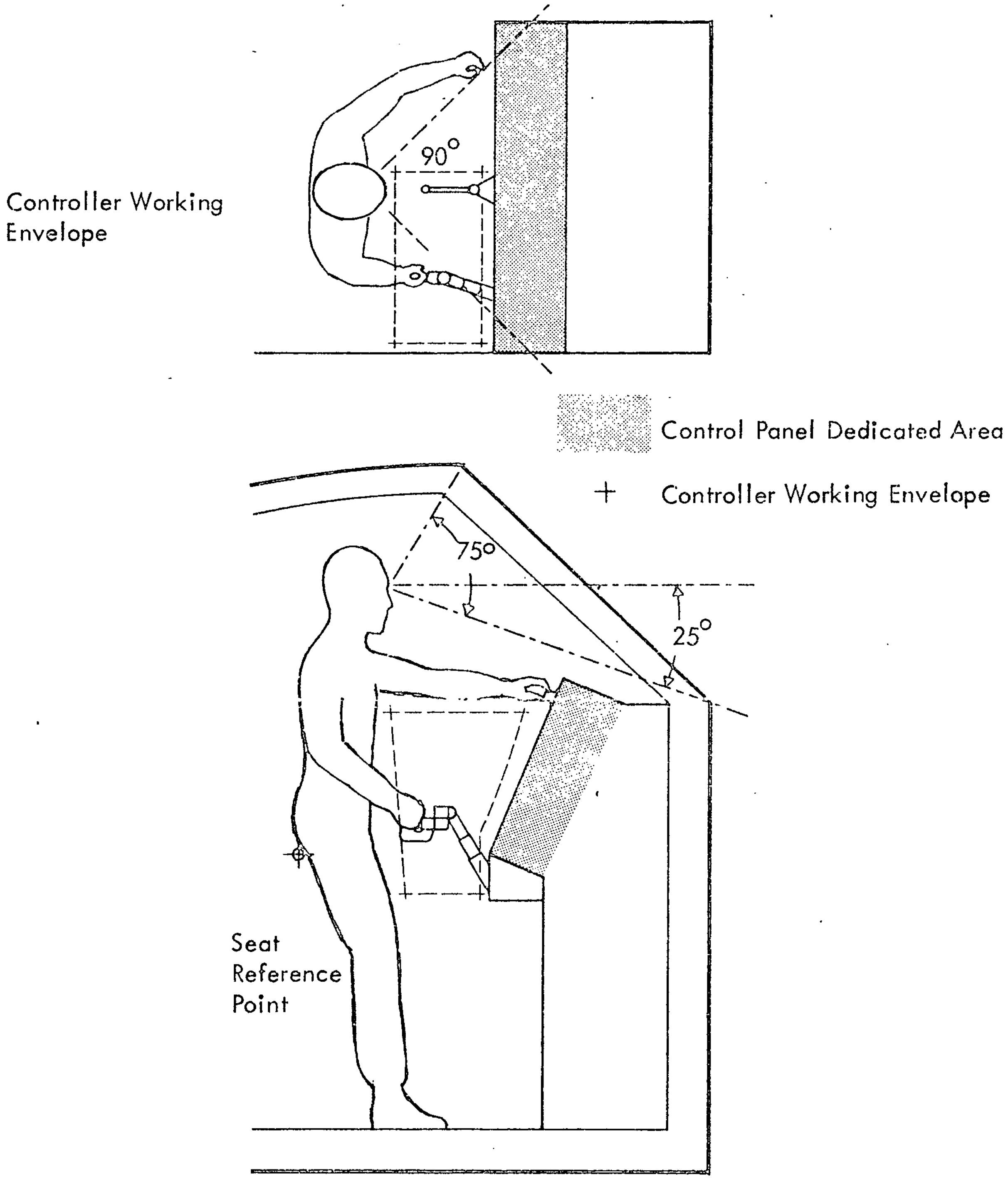

FIGURE 6.4-16.
MASTER CONTROLLER USED FOR DEXTEROUS
END EFFECTOR CONTROL

0132-10049

then performs the coordinate and force transformations to:

(1) Control the end point/wrist assembly of the slave in a position-position force reflecting mode (note that the master/slave linear movement ratio is less than unity, but is constant), and

(2) Reflect the net slave reaction force and torques into appropriate cabin oriented x, y, z, θ_x, θ_y, θ_z forces and torques on the operator grip.

For main boom end point rate control/force reflecting position-position wrist control the controller arm is locked in a "stationary" x, y, z joystick transducer (not shown). The concept is that the transducer sense only the x, y, z operator force rate inputs. Careful design in conjunction with simulation studies is required to configure the transducer, master controller and control circuitry such that the operator rate input forces are decoupled from the force reflected wrist torques. If extreme difficulty is encountered in achieving the necessary decoupling, a two hand control approach can be used where say the left hand controller is used for the x, y, z force rate input and the right hand controller is used for the wrist position-position force reflecting controller.

6.5 Visual System Analysis and Design

6.5.1 Viewing Mode

Television direct viewing and optical instrument viewing (in case of TV system failure) will be used. The optical instrument will consist of a stereo-periscope with variable field magnification (zoom) and dual field. The television system will have relatively high resolution (of the order of 1200 lines), in order to assure adequate information handling capability.

6.5.2 Viewing Geometry and Camera Positioning

The manipulator operator on the 040A shuttle has an aft oriented direct overview of the cargo bay with viewing angles of approximately up 55°, down 20°, left 45° and right 45° (see Figure 6.4-1). There are no side, overhead or forward looking windows. For many cargo handling/ satellite operations this direct viewing available will be adequate for overseeing the operation, but it may or may not be adequate for end connector/end effector engagements, etc. It is anticipated that as a minimum a single field, monocular black and white TV camera at the distal end of the boom will be required for such an operation. For more complex and precise operation the selected visual system will be required and with it the complete upper hemisphere will be accessible by use of the auxiliary viewing boom and dedicated fixed location single field camera which will provide additional coverage of particular zones of interest such as remote areas of the cargo bay. The main boom camera will be able to provide a shuttle bottom side overview, however, detailed inspection in most areas will not be possible.

The complete visual system will be required for the space station and with the array of root points on all the modules (see Figure 3.5-3) complete visual coverage of the entire station will be possible. (It will be necessary to rotate the solar panels to cover all areas on it).

6.5.3 Camera Features

6.5.3.1 Image Tubes

Silicon vidicons will be used as image tubes for complete safety against incapacitation by direct or specularly reflected solar illumination. For the stereo cameras, the tubes, in order minimize creating spurious features in the stereoscopic visual field,will be hand picked to obtain the minimum number of defects possible for the available state-of-the-art. Distortion compensating circuitry will be used to improve image quality.

6.5.3.2 Image Brightness Control

In order to cope with the problem of high brightness gradients in the same field, techniques will be used in the circuitry, such as anti-comit tail gun and automatic beam control in combination with an automatic iris and a concentric step neutral filter in the lens for increasing iris attenuation range (as developed by Zoomar).

6.5.3.3 Automatic Focusing

Automatic focusing is necessary with zoom lenses at narrow fields (long focal lengths) because of the reduced depth of field. It becomes even more stringent with stereoscopic cameras where convergence on the observed object has to be maintained. In the absence of automatic focusing and convergence, the operator would be burdened with one or even two additional controls (if focus and stereo convergence are not coupled). The automatic focusing system will analyze the video signal obtained by dithering the lens along the optical axis (Figure 6.5-1). Maximum local light intensity indicates the position of the optimum focus plane. As shown at CDC by John Chatten,(1) the slight defocusing produced by focal plane dither cannot be sensed by the observer.

6.5.3.4 Lens Field

The cameras will be provided with varifocal (zoom) lenses under operator control. A zoom ratio of 10:1 with a typical focal length range of 15 mm to 150 mm represents a horizontal visual angle range

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(1) Personal communications between J. Chatten of CDC and F. Schwartz of MBA, July 1971.

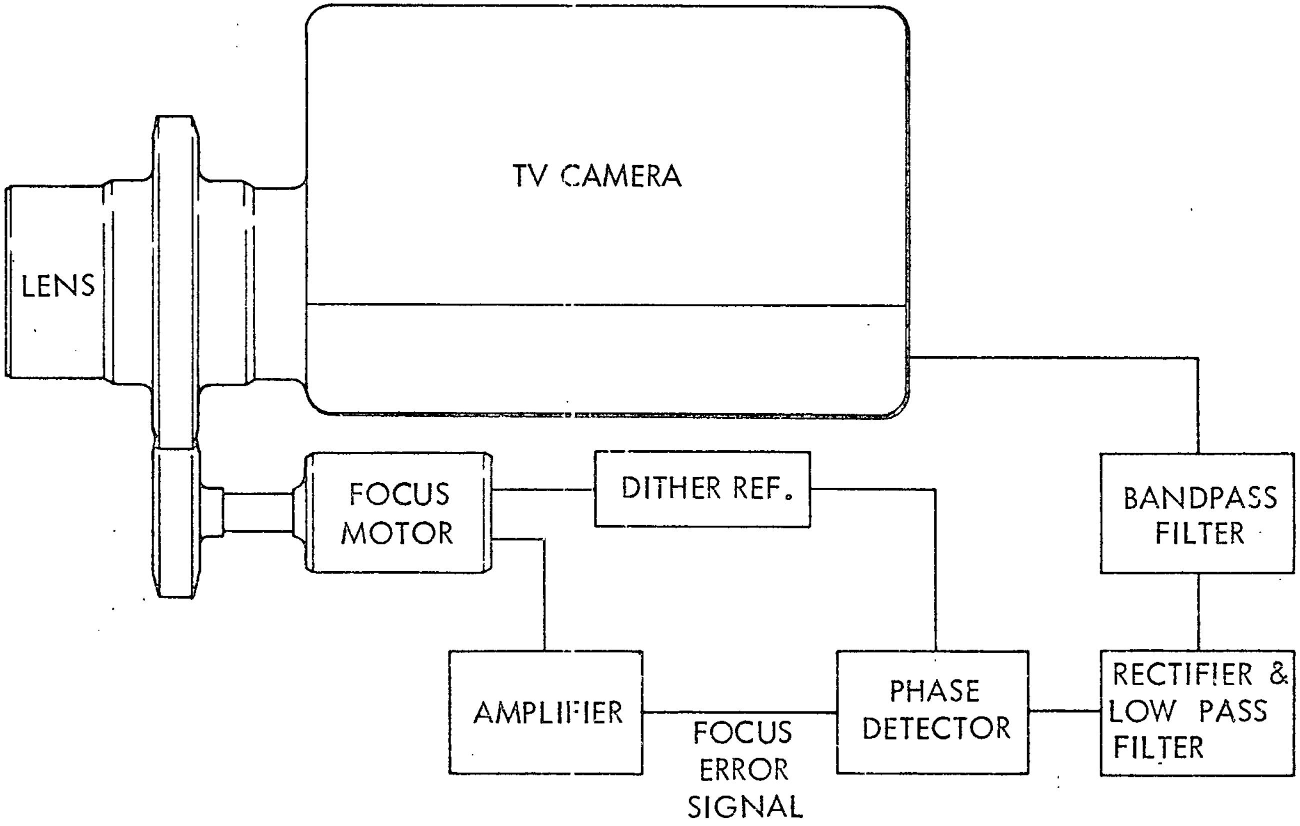


FIGURE 6.5.1.
VIDEO AUTO-FOCUS CONCEPT

from 46° to 4.6°. Development is needed on a zoom lens capable of focusing at distances closer than the 4 feet minimum presently available on commercial remote controlled zoom lenses and also on lenses with complementary fields for foveal application.

6.5.3.5 Color

Color will be provided in a sequential mode with a "color wheel" system in order to minimize the number of cameras used. The color wheel will be capable of being switched in and out of the system, since it is expected to be used only for inspection tasks. The framing rate with a color wheel is 1/3 that for black and white (with the same camera) and therefore color is not as desirable as black and white for dynamic situation. Inspection almost always involves a static situation so that the reduced framing rate does not degrade viewing resolution.

6.5.3.6 Special Devices

Dedicated devices for special tasks, such as flexible and orientable fiber optics inspection probes (endoscopes), tele-extenders and macro attachments for extending the functioning range in the near and far field of the camera lenses and berthing targets will be provided as required.

6.5.3.7 Fail-Safe Feature

The distance, zoom iris and stereo convergence control will be spring loaded or equivalent so that in case of actuator failure the lens controls should revert to a minimum useful profile comprising maximum field of view (minimum focal length) for the zoom, fixed aperture, hyperfocal distance focusing (lens focused to provide a reasonably sharp image over a range extending from a few feet to infinity for a given iris aperture). This will provide a minimum useable configuration for the television camera in case the video channel continues to be functional and the lens controls fail.

6.5.4 Visual Modes

6.5.4.1 Eye Acuity Matched TV With Operator-Controlled Field Scan (Foveal Technique) for Optimizing Resolution

The inherent resolution limitation of television systems can be overcome by presenting to the observer a display that is matched to the visual acuity of the eye. The maximum acuity, corresponding to approximately one minute of arc resolution is found only at the center of the visual field, covered by the eye fovea. Off-axis, the acuity of the eye decreases rapidly. The human observer perceives a high resolution image of the visual world by continual scanning of the visual field with the critical seeing being done always with the fovea (see Figure 6.5-2).

In the foveal television system, the visual field is divided into a central, high resolution area, surrounded by a peripheral, low resolution area. Scanning of the visual field is performed by the television cameras, controlled by the operator through a servo loop.

The system is essentially a double television system, comprising a narrow, high resolution central field and a wide field low resolution peripheral field that are made to register as concentric and adjacent portions of the same field of view. The operator keeps his eye trained on the central high resolution field. Thus, if a 1200 line TV system is used, the display presents a resolution equivalent to a 4800 line system for the whole visual field at a savings of 7/8 in. bandwidth and correspondingly in circuit complexity and camera size.

The two cameras will be mounted parallel and adjacent. The optical axes of the cameras will be brought to coincidence using mirrors. The two cameras will be mounted on a common pan and tilt assembly. A beam splitter (partially reflecting mirror) will be used to bring the fields of the two cameras into coincidence. The zoom lenses on both cameras will be synchronized in order to maintain field registration.

The system includes an "origin transfer" feature that changes the angular speed ratio of "position control input" to "angle of camera rotation" with focal length so that the apparent motion of the visual field on the display is kept in a 1:1 ratio with the operator's control movements. This is to provide good control at large focal lengths.

6.5.4.2 Stereoscopy

Stereoscopy is needed for operation of the dexterous manipulator, as well as for any task involving close matching. The stereoscopic system used will be of the split-field type, in order to minimize the number of cameras and to eliminate problems of camera and monitor matching. Image quality and stereoscopic perception will be improved by elimination

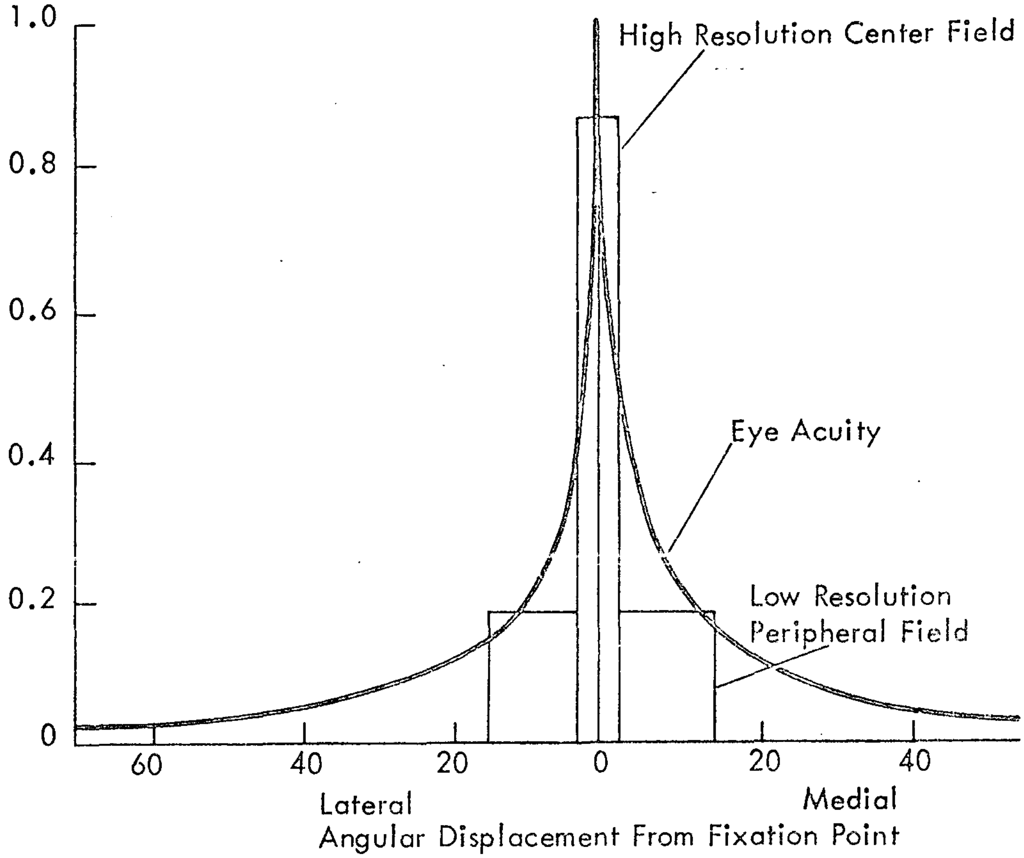


FIGURE 6.5.2
PERIPHERAL VISUAL ACUITY AND RESOLUTION OF DISPLAY FIELDS

of non-stereoscopic disparities of the video display and by increased stereoscopic acuity through increased horizontal resolution. A 90° image counter-rotation technique developed at MBA will be used for this purpose. (See Figures 6.5-3, 6.5-4 and 6.5-5).

The stereoscopic system will have a fixed base (the separation distance between the stereo aperatures on the camera) since the primary viewing stereo camera will always be located within a normal working range of the work area.

6.5.4.3 Stereo-Foveal

A maximum flow of visual information needed for the dexterous manipulator's tasks will be provided by a stereo-foveal system combining the two previously described techniques. In this embodiment, only the narrow (foveal) field will be stereoscopic, since stereoscopic perception is concentrated mostly in the central part of the eye's field of vision. A split field technique will be applied making use of a single camera and a single monitor for both stereoscopic fields in order to eliminate any problems connected with electronic mismatch between the two images and also reduce complexity. An aspect ratio of 2:1 will be used to provide two square stereoscopic fields. 90° field counter-rotation will be used for symmetric image registration on the image and cathode ray tubes, to eliminate nonstereoscopic image disparities and increase horizontal resolution for optimum stereoscopic acuity.

6.5.5 Camera Selection

Two types of cameras are used in the visual system and they are located as follows:

TYPE 1	Features	Location
	Stereo foveal dual field	Main boom (wrist and shoulder)
	Black and white/color	"Head" of dexterous end effector
	Auto focus, brightness and convergence	Tip of auxiliary viewing boom
	Remote zoom	

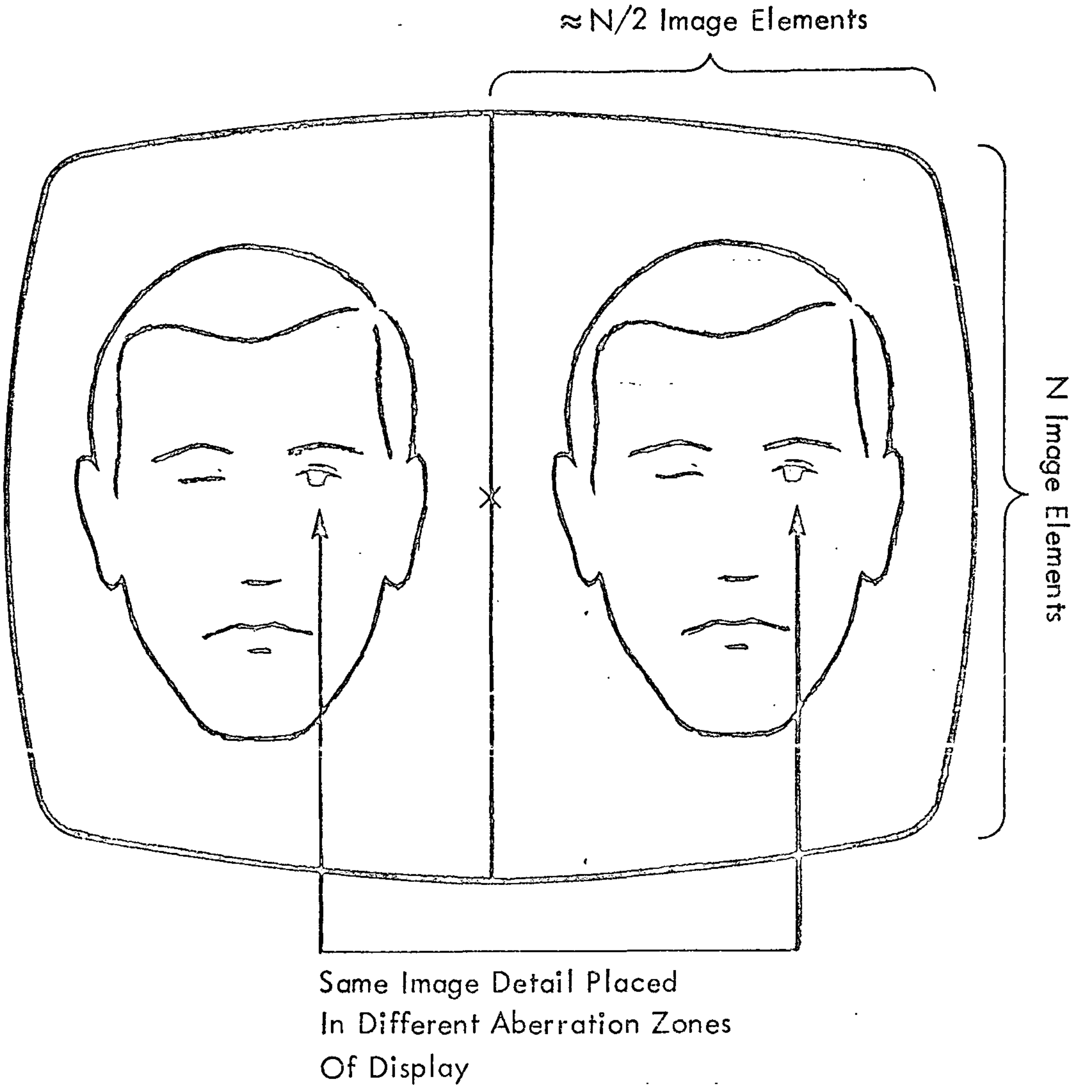


FIGURE 6.5.3.

SPLIT FIELD STEREOSCOPIC VIDEO DISPLAY WITH NON-STEREOSCOPIC IMAGE DISPARITIES AND HORIZONTAL RESOLUTION LOWER THAN VERTICAL RESOLUTION

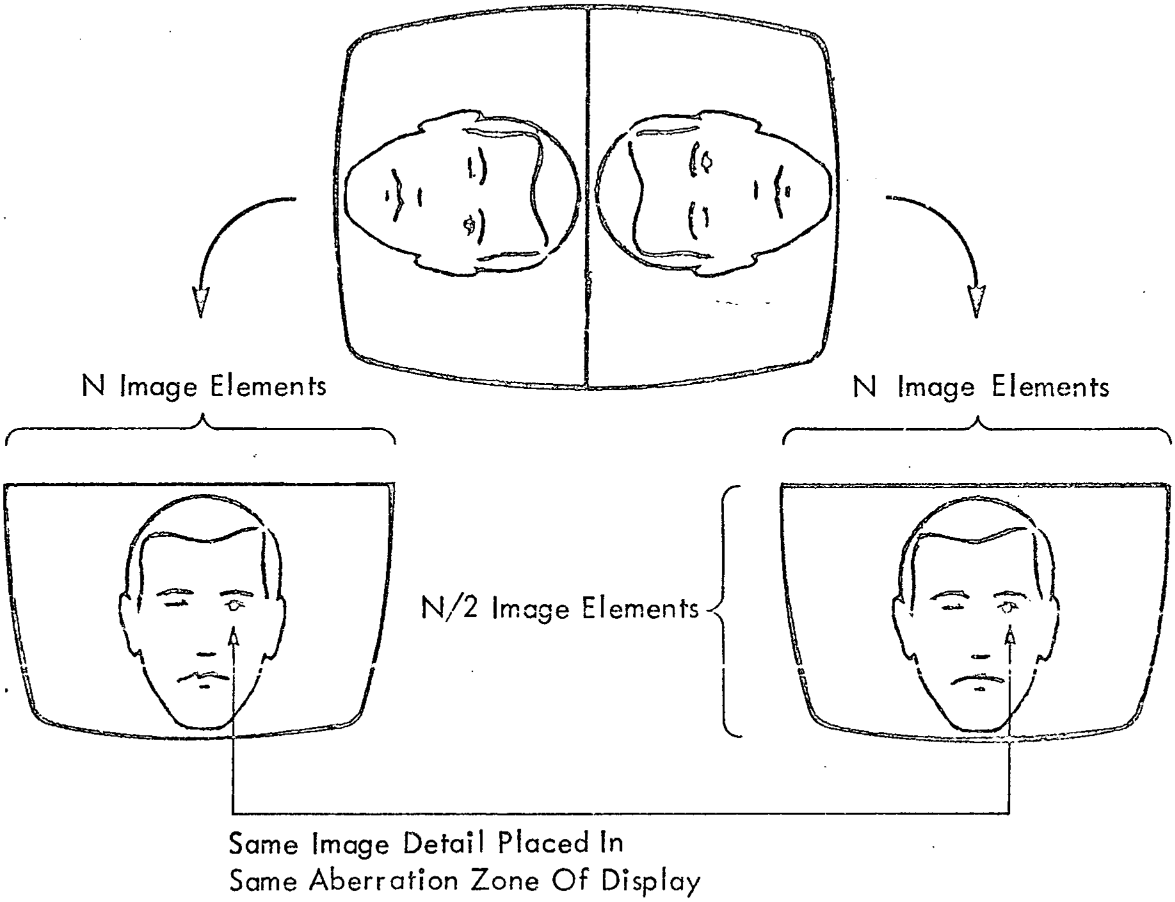
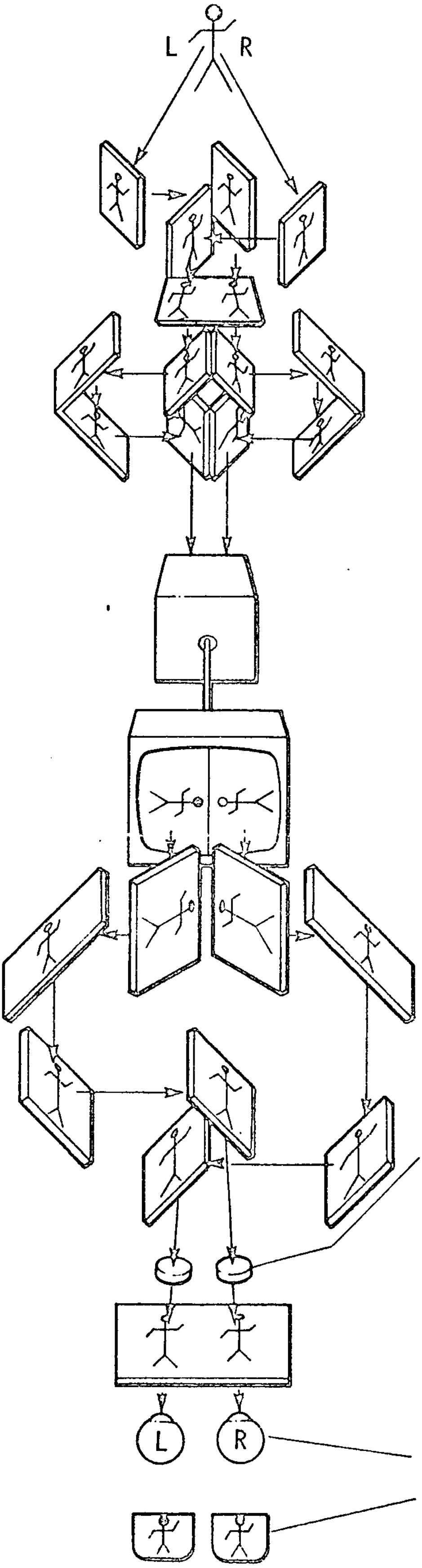


FIGURE 3.3-5
SPLIT FIELD STEREOSCOPIC VIDEO DISPLAY 90° IMAGE COUNTERROTATION WITHOUT NON-STEREOSCOPIC IMAGE DISPARITIES AND HORIZONTAL RESOLUTION HIGHER THAN VERTICAL RESOLUTION FOR ECONOMY OF BANDWIDTH



Object

Stereoscopic Adaptor
Produces two stereoscopic views of the object

Mirror System
Rotates images by 90° into opposite directions so that they register simetrically on the camera image tube to get similar distortions. Thus there will be no image disparity produced by distortion. Only image disparity is stereoscopic disparity.

TV Camera With Narrow Field Lens.

T. V. Monitor
Symmetrically registered images. The lateral resolution of the image (determines stereoscopic acuity) is higher than the vertical resolution.

Mirror System
Rotates images by 90° in opposite directions.

Negative Lenses
To form a virtual image of screen at the same distance as the wide field monitor screen and covering the desired foveal field angle.

Beamsplitter
Leaving free view beyond to the wide field monitor screen. The mirror system is aligned so as to make the left and right virtual images coincide at the peripheral monitor screen.

Observer Eyes

Stereoscopic Images seen by observer.

FIGURE 6.5.5.
MIRROR SYSTEMS AND IMAGE COUNTER ROTATION

TYPE 2	Features	Location
	Monocular, single field Black and white Auto focus, brightness Remote zoom	Cargo bay, berthing ports (As required)

The Type 1 camera actually includes two cameras slaved together as shown in Figure 3.3.-4 and it includes all of the features described in Section 6.5.3. A block diagram illustrating the functional arrangement of the camera components and of the display system (discussed below) is shown in Figure 6.5-6. The Type 2 camera consists only of a single camera with the features indicated.

6.5.6 Displays

The displays will be panel mounted in order to dispense with operator encumbrance (see Figure 2.3-7). The stereoscopic display will be a parallax stereogram using alternating vertical strips for the left and right eye images and a cylindrical lens array for image separation (see Figure 6.5-7). The right and left stereoscopic images will be scanned with spaced scan lines. The space between scan lines will be slightly larger than one scan line (the difference being needed for avoiding line overlap within the system tolerance limits). The pair of stereoscopic images will be rear-projected on the display screen in such a way that the scan lines interlace. On the face of the screen an array of cylindrical lenses, each of them having a width of two scan lines, will visually separate the right and left eye stereoscopic images for the observer. The lenses will be designed to provide an optimum operator position in front of the display and will provide freedom of head movement within a range of approximately 1 foot.

Computer generated mobile stereoscopic depth marks in the display will be projected into the observer's field of view to provide a range-finding capability.

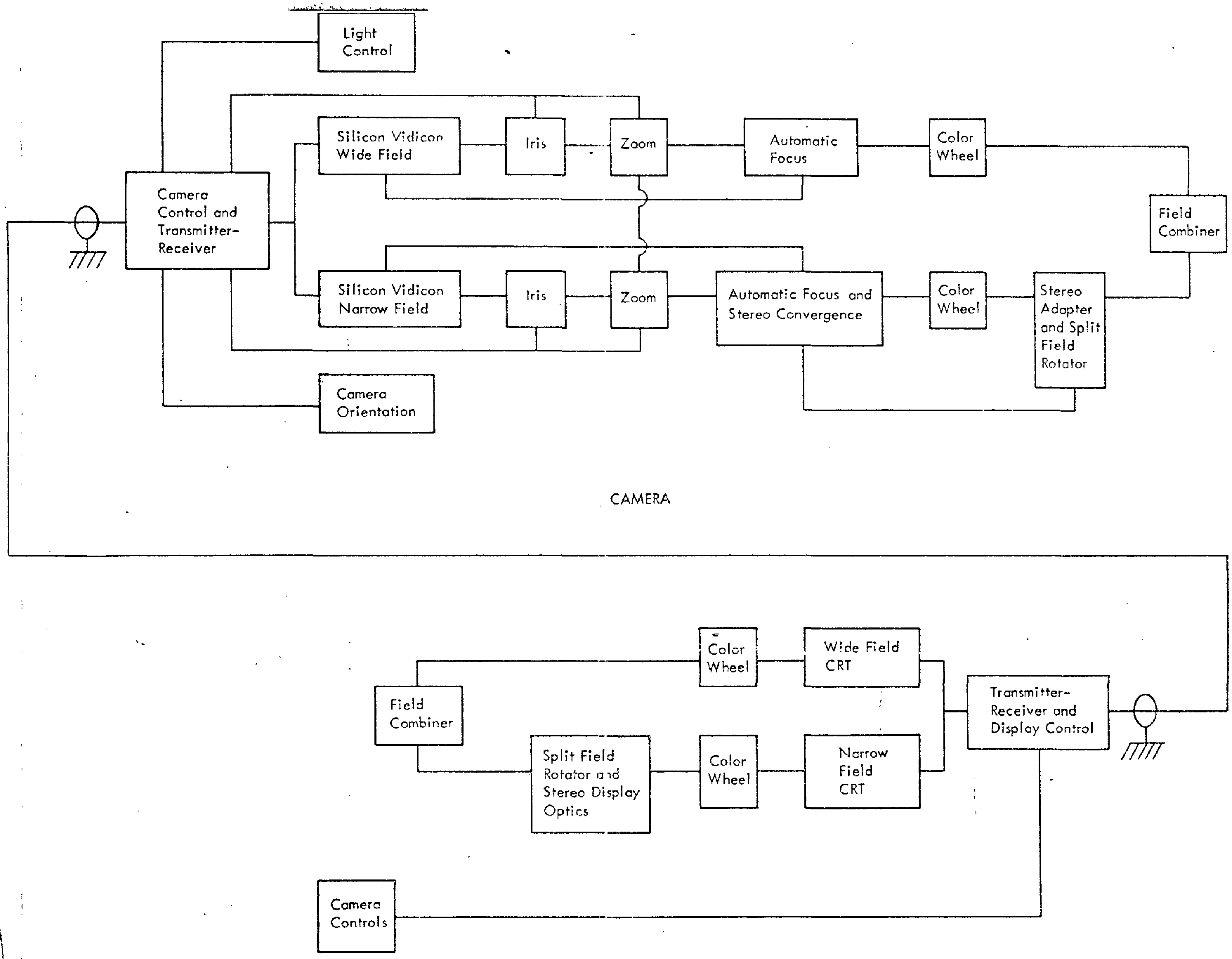


FIGURE 6.5.6.
THE STEREO FOVEAL REMOTE VIEWING SYSTEM
FUNCTIONAL BLOCK DIAGRAM

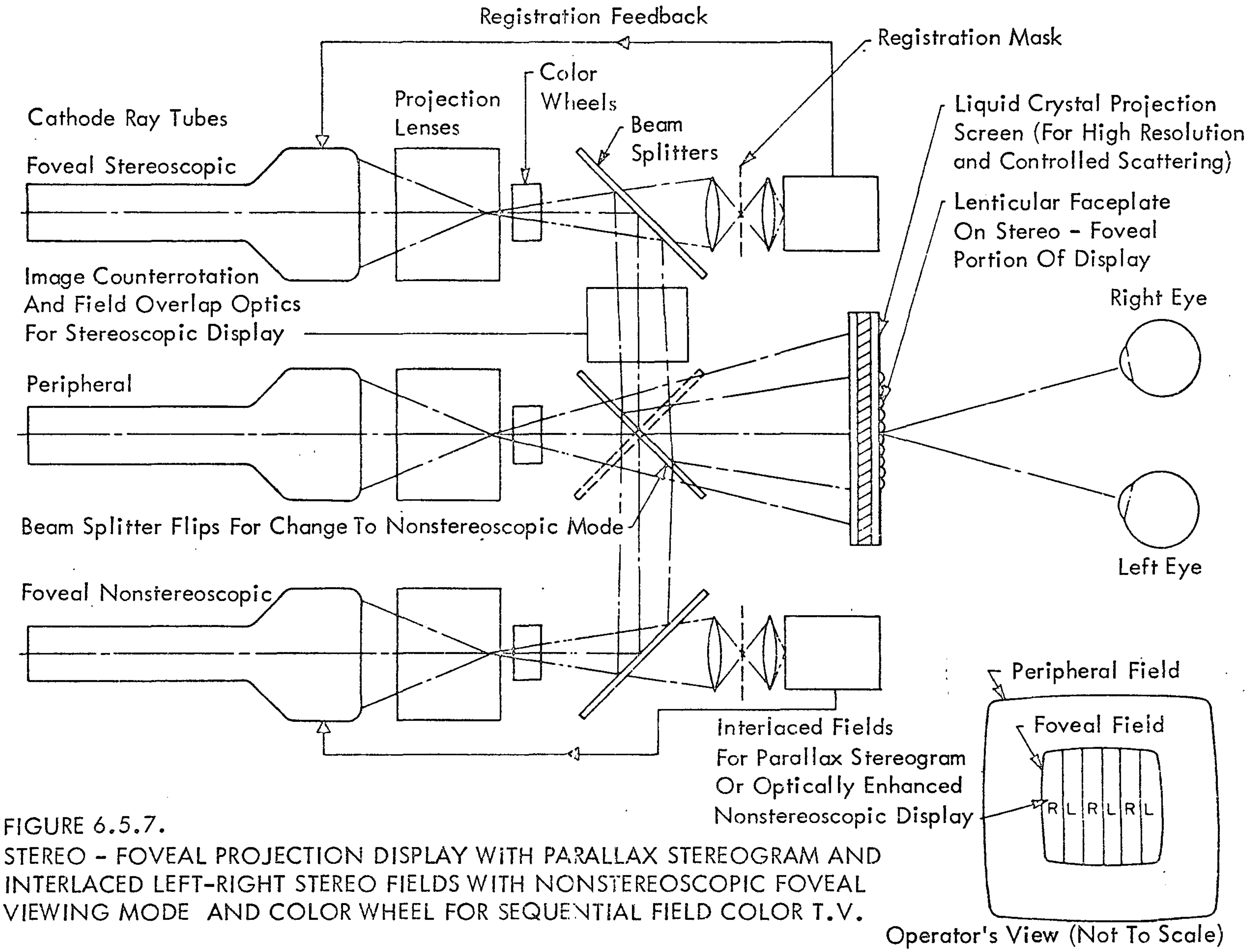


FIGURE 6.5.7.
STEREO - FOVEAL PROJECTION DISPLAY WITH PARALLAX STEREOGRAM AND INTERLACED LEFT-RIGHT STEREO FIELDS WITH NONSTEREOSCOPIC FOVEAL VIEWING MODE AND COLOR WHEEL FOR SEQUENTIAL FIELD COLOR T.V.

In the non-stereoscopic single-field mode, when only the peripheral camera is used, the center of its image will not be blanked out. In this case, the cylindrical lens array will serve as an image enhancer by making the eyes see alternate image element groups. This stereoscopic image enhancement technique works by introducing artificial disparity between the images seen by the observer's eyes. An illusion of stereoscopy is created that facilitates observation of the display. The details seen in the display appear to be arranged in a three-dimensional, rather than a two-dimensional space. This should enhance visual perception of image details.

The use of the cylindrical lens array demands critical registration of the scan lines, so that they cannot wander out of the field of the assigned cylindrical lenses. Adequate image registration techniques have been developed in the field of color television. This knowledge will be used in the design of the image registration control. Figure 6.5-7 depicts a device using a stripped mask and a photomultiplier monitoring the presence of signals at all times along the registration mask to maintain registration.

The rear projection screen uses a liquid crystal for the scattering medium to provide increased resolution and controlled scattering angle for maximum luminous efficiency of the display.

Normally separate monitors will be used for display of non-foveal imagery. Switches will be provided to make possible display of the output, however, of any camera to any monitor.

6.5.7 Camera Controls

Camera orientation will be controlled by the operator's eye in order to keep his limbs free for other tasks and not to demand any conscious effort. The relative position of the reflected images of a near infrared light source projected on the eye are used to sense changes in the direction of the observer's line of sight (as in the eye tracking devices).

The observer is looking at the center of the foveal display. The control system will be set in such a way that when the operator persists in looking off center, the camera's orientation is changed towards the direction the operator is looking. Zoom can also be controlled by coded eye positioning, such as looking at a certain portion of the display following a determined pattern; however, this technique requires some conscious control and must be compared with other techniques.

6.5.8 Television Picture Quality

Depth of field will be maximized by using an automatic diaphragm, computer controlled, in conjunction with the electronic tube sensitivity control in such a way as to have minimum diaphragm aperture combined with optimized large characteristics such as grey scale.

Automatic beam intensity control and anticomet tail techniques will also be used for high contrast situations. Grey range will be maximized because of its importance in color wheel TV. Motion rendition will be optimized by choice of low lag image tubes and by high mobility of optical axis, combined with the automatic focus and steroscopy. The low speeds at which the manipulator will move will contribute to image smear reduction. Geometry distortion will be improved by use of distortion compensating circuitry and fiber optics faceplate display tubes for image plane flattening.

6.5.9 Illumination

6.5.9.1 Earth Shadow

The sensitivity of the silicon array image tube requires only approximately 20 watts per square meter of illuminated target area as input to the light source. 1500 watts will be needed to light an area corresponding to an entire module. The lighting will be provided by a battery of three 500-watt lamps, to assure adaptability of lighting power to lighted areas as well as increased reliability. Halogen cycle incandescent lamps will be used. (These lamps use tungsten iodide vapor to redeposit tungstun on the filament during operation, thereby permitting increased filament temperature and greater radiant output with long filament life).

"Tailored beam" illumination optics of high collection efficiency will be cited to provide highest source-to-beam conversion efficiency and uniform image plane illumination. For work in the earth's shadow, wide beam illumination of relatively low intensity is sufficient. For work in sunlight, narrow beams of high intensity are needed to illuminate the shadowed objects because of high intensity of sunlight. Narrow beams are also to be used with narrow fields of view for obvious economy reasons. Variable beamwidth can be obtained either by relative movement of source and illumination optics or by using special lamps with various beam angles. For reliability reasons, only two beamwidths (narrow and wide) will be used in twin filament lamps, so as to obtain electric switching which is simpler and more reliable. The lamps will be mounted near to the cameras and pointed parallel to the optical axis. They will be used progressively with distance to the target to be illuminated (1 lamp for minimum distance, 2 - 3 lamps for maximum distance). At the same time, the spot-flood switching mode will be used. The foveal cameras will carry three lamps, the fixed cameras will carry one lamp.

An emergency illumination system will be provided in the form of a narrow beam, hand-held light to be used from inside through windows.

6.5.9.2 Sunlight

The illumination range under which the TV system will operate in sunlight cannot be accommodated by any available image tube on a single frame. Since artificial illumination sufficient to balance sun illumination would need at least 70-80 watts/m^2 of input power to the lights even when using filters on spectral line light sources, the foveal TV technique will be used to solve the brightness gradient problem (Figure 3.3-3) without having to make recourse to high-power lighting by sighting on the dark areas with the foveal camera only and restricting its field of view by zooming to eliminate the large brightness gradients from the field of view of any of the single cameras. Even if this ideal condition cannot be met, the presence of over-or-under-exposed areas in the same frame of the foveal or peripheral of the foveal system camera can be compensated for by scanning with the cameras. This technique also permits the use of the low intensity "night" light sources to increase the illumination of the dark areas. The choice of specific image tubes will be made at a later time, due to the continuous improvement of the state-of-the-art.

6.5.10 Dedicated Viewing Boom

The dedicated viewing boom must be able to attach to the root points used by the main boom and receive control signals and power and transmit TV signals through it. Furthermore, the viewing boom must be configured such that it can be moved about the shuttle or station by the main boom.

The general features of the viewing boom are illustrated in Figure 6.5-8. An astromast type boom (a type developed by Astro Research Corporation for Lockheed to deploy a Lockheed designed space station solar power panel) has been selected.

The boom consists of a unique, extendable truss type triangular shaped column erected and retracted by a rotating mechanism incorporated into the storage drum (see Figure 6.5-9). In the collapsed configuration the mast is completely contained in the storage drum which for the viewing boom application, would be about 22.8 (9 in.) in diameter by 1.22 m (4 ft.) in length.

The shoulder cluster for the boom consists of the same end connector used in the main boom plus roll and pivot joints (in that order). A pan, tilt and roll cluster are located at the distal end of boom to orient the camera assembly in any desired direction with any desired "horizon".

The boom actuators located at either end will be DC driven electric motors with harmonic drive transmissions. (Since the translation velocities for these joints are very small and the only loads are inertial loads of the camera, standard harmonic drive units can be used.) The actuator for the extendible section will also be a DC electric motor which drives the drum type erecting and contracting mechanism. The tip force of this boom will be about .5Kg (1 lb). The maximum torque at the bottom actuator will therefore be 81Nm (60 ft/lb) for a 18.3m (60 ft) long TV boom.

The advantage with using an extendible boom is that during transportation to space and while the TV boom is not being used, it will take up very little room. Having it retractable also makes it much easier to move from root point to root point.

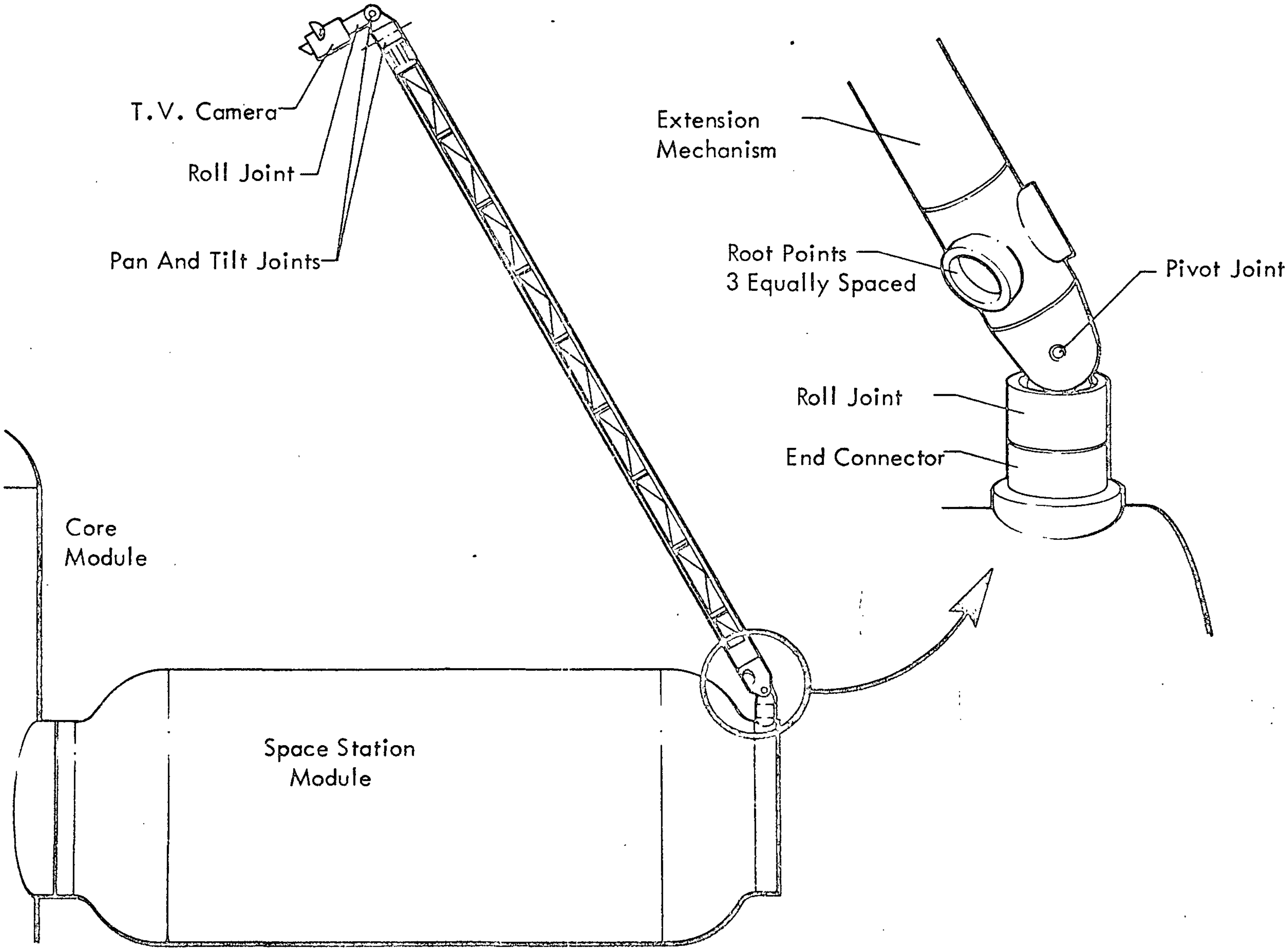


FIGURE 6.5-8.
DEDICATED VIEWING BOOM SCHEMATIC

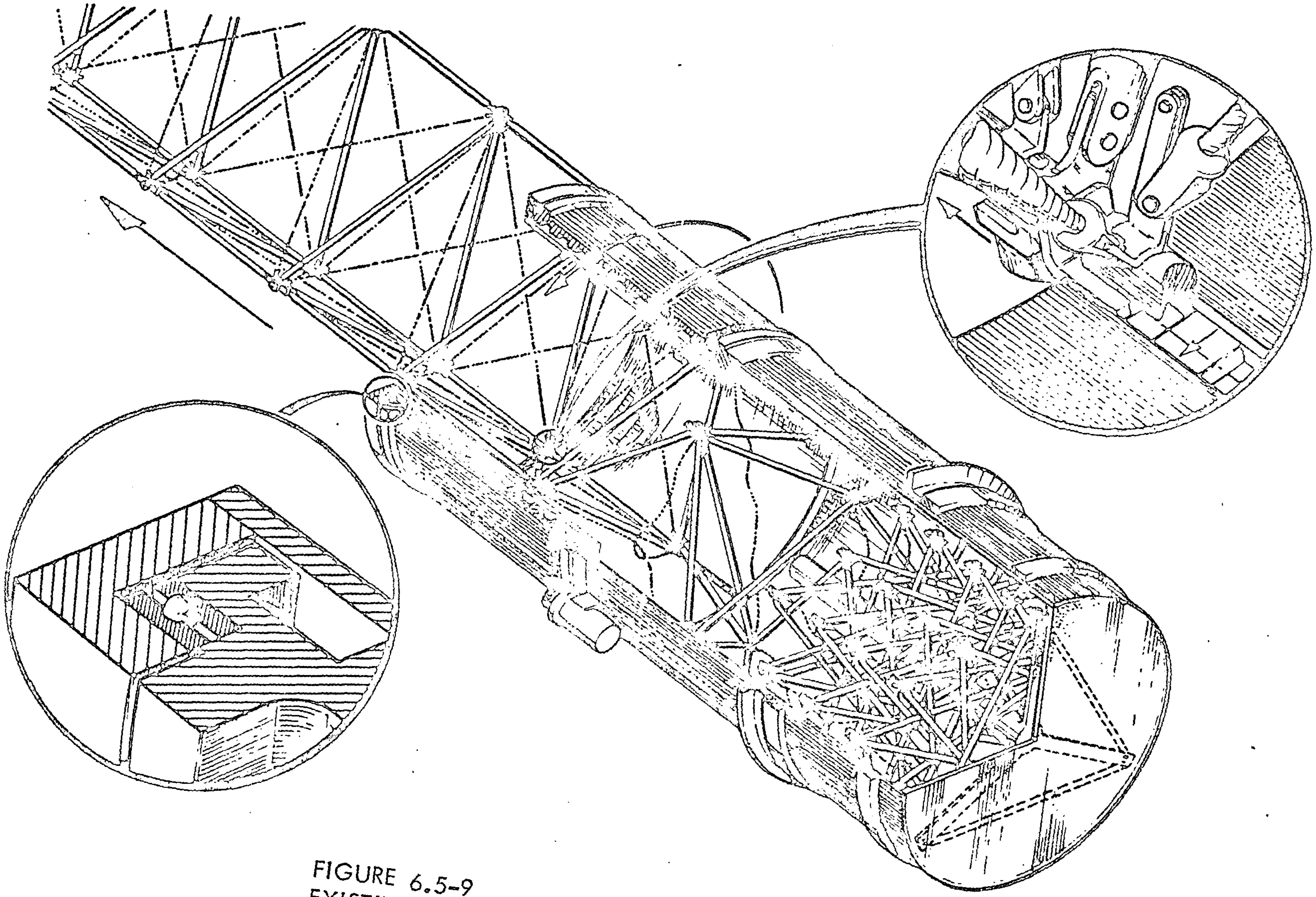


FIGURE 6.5-9
EXISTING LMSC ASTROMAST CUTAWAY
DETAILS AVAILABLE IN TECHNOLOGY EVALUATION
REPORT LMSC-A981486

The cross-section of the extended triangular shaped boom can be a circumscribed in a 17.8 cm(7 in.) circle. The material used for the structural members will be 0.32 cm(0.125 in) beryllium rods. Such a boom will only weigh 0.3 Kg/m (0.2 lbs/ft). For the 18.3m (60 ft) long boom this would only be 5.5 Kg (12 lbs). The actuator for the extendible boom weighs 11.4 Kg (25 lb).

The natural fundamental frequency of the boom with an 18 Kg (40 lb) camera assembly at the end is about 0.1 Hertz. Oscillations of the boom are not anticipated to be a problem but this area requires further detailed study and design.

6.6 Boom Control System Analysis and Design

6.6.1 General

This section describes the computer control system which will regulate movements of the boom. It treats the functional design of the software, operation of the various program modules, and the supporting computer hardware. The three major functions of the computer system are on line monitoring, supervisory control, and end-point control.

The end point and supervisory control functions are described in Section 3.3.4, Volume II. The dynamic monitor program follows the movements of the boom and checks for impending collisions between a boom component and other structures. Collisions are predicted by matching the output of an algorithm which continuously projects boom position with a map of the environment stored in computer memory. The boom is automatically halted if a collision impends. The "look-ahead" distance is determined by dynamic considerations.

The following sections describe in detail the realization of these three program functions.

6.6.2 End Point Control

6.6.2.1 Program Concept

Figure 6.6-1 illustrates schematically the orientation and position of the boom at an arbitrary point in space. Euclidian coordinates are superimposed in the figure with an origin at the fixed end of the boom. In designing the control program the following constraints are set:

- The computer resolves the motion rates of the elbow $\dot{\beta}$, shoulder elevation $\dot{\alpha}$, and shoulder rotation $\dot{\varphi}$ and orientation of the elbow, $\dot{\gamma}$ into the specified Euclidian movement $[\dot{X}, \dot{Y}, \dot{Z}]$.
- For computational purposes, the center of rotation and orientation of the end cluster of the boom is considered as the end point.

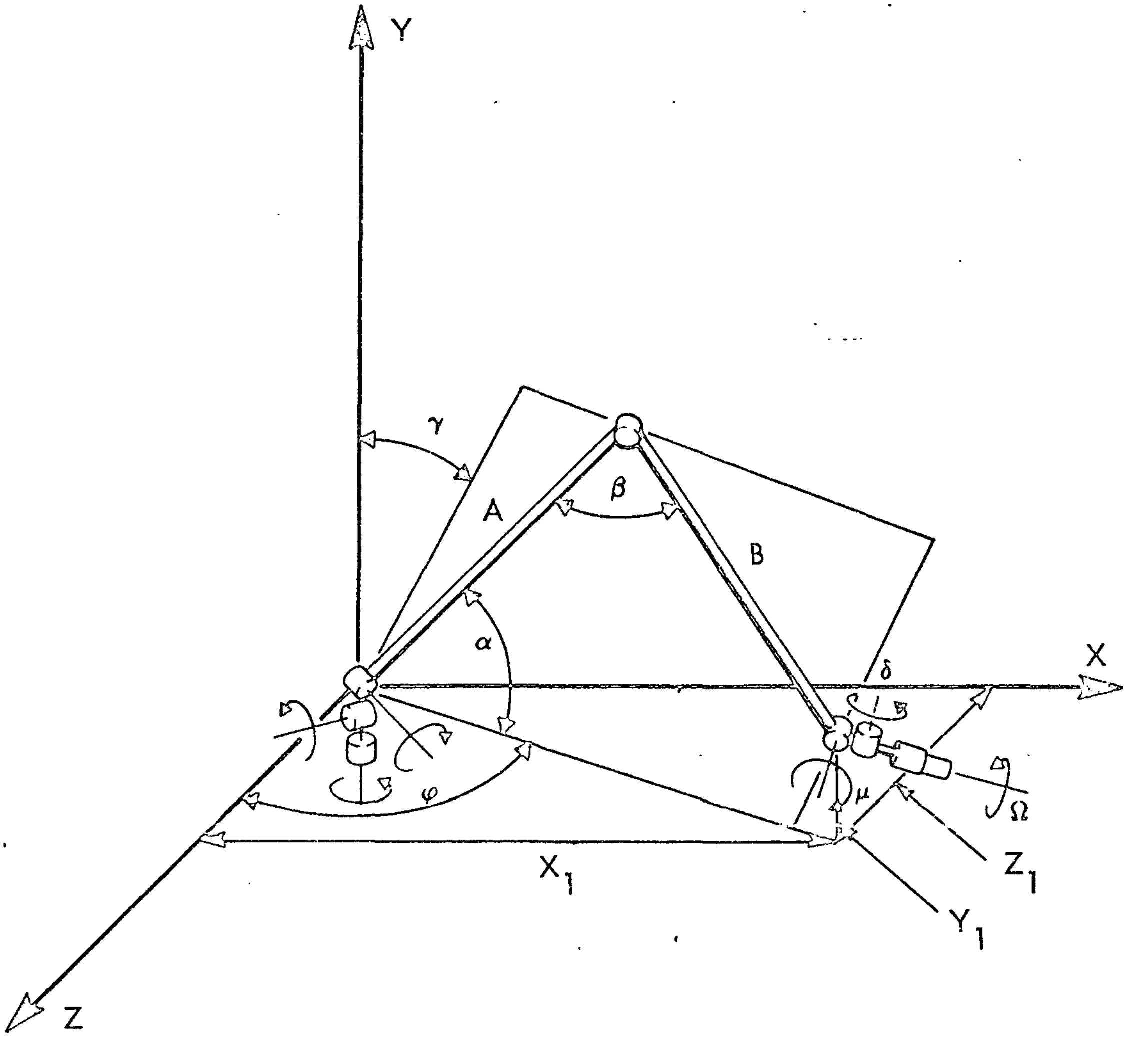


FIGURE 6.6-1
BOOM COORDINATE SYSTEM

- Control function for orientation and rotation of the end cluster will be provided through a programmed coupling algorithm. End cluster orientation will be kept constant with changes in β, α, φ and γ.

The main function of the program is to transform motion rates along Euclidian coordinates into joint angle rates. Two transformation techniques are provided. The first involves direct solution of the mathematical equation that maps Euclidian rates $[\dot{X}, \dot{Y}, \dot{Z}]$ into angular rates $\dot{\alpha}$, $\dot{\beta}$, $\dot{\varphi}$ and is limited to motion in three degrees of freedom. The second algorithm involves a numerical solution and allows for mapping the Euclidian rates into four degrees of freedom. The development of each of the transformation techniques for end point control can be given as follows.

6.6.2.2 Direct Transformation

The position of the boom end point in space is defined by a vector $\overline{X}$ where $\overline{X} = [X, Y, Z]$. The joint angle positions are defined by a vector $\overline{\theta}$ where $\overline{\theta} = [\alpha, \beta, \varphi]$.

The relationship between $\overline{X}$ and $\overline{\theta}$ can be then written as:

$$\overline{X} = f(\overline{\theta}) \qquad (1)$$

If Expression (1) is differentiated with respect to time we obtain (Whitney 1969)

$$\frac{dx}{dt} = J(\theta)\,\dot{\theta} \qquad (2)$$

where $J(\theta)$ is the Jacobian matrix which defines the partial derivitive of $\overline{X}$ with respect to $\overline{\theta}$. The required solution must yield the angular rates in terms of the end point motion rates. To obtain this solution Equation (2) can be rewritten as:

$$\dot{\overline{\theta}} = J^{-1}(\overline{\theta})\,\dot{X} \qquad (3)$$

Whitney, D.E. "Resolved Motion Rate Control of Manipulators and Human Prostheses", IEEE Transaction on Man-Machine Systems, Vol.MMS-10, No. 2, June 1969

It is normally quite difficult to compute the inverted Jacobian matrix. However, for the case at hand, the Jacobian is only a 3 x 3 matrix, and can be numerically inverted in real time.

Application of the above concept to the boom control can be done as follows:

Referring back to Figure 6.6-1, f $(\bar{\theta})$ can be written as

$$f(\theta) = \begin{bmatrix} A & [\cos\alpha - \cos(\alpha+\beta)]\sin\varphi \\ A & [\sin\alpha - \sin(\alpha+\beta)]\cos\gamma \\ A & [\cos\alpha - \cos(\alpha+\beta)]\cos \quad \sin\gamma \end{bmatrix} \tag{4}$$

Calculating the Jacobian, the following matrix is obtained:

$$J(\theta) = A \cdot$$

$$\begin{bmatrix} [\sin\alpha + \sin(\alpha+\beta)\sin\varphi] & [\sin(\alpha+\beta)\sin\varphi] & [\cos\alpha - \cos(\alpha+\beta)] \\ [\cos\alpha - \cos(\alpha+\beta)\cos\gamma] & [-\cos(\alpha+\beta)\cos\gamma] & 0 \\ [\sin\alpha + \sin(\alpha+\beta)\cos\varphi\sin\gamma] & [\sin(\alpha+\beta)\cos\varphi\sin\gamma] & [-\cos - \cos(\alpha+\beta)\sin\varphi\sin\gamma] \end{bmatrix} \tag{5}$$

Having the above matrix, transformation of the end point rates into angular rate can be estimated numerically for a given angular position $[\alpha, \beta, \varphi]$ and a rate $[\dot{X}_1, \dot{Y}_1, \dot{Z}_1]$ a corresponding angular rate $[\dot{\alpha}, \dot{\beta}, \dot{\varphi}]$ will be generated. It should be noted that although the angle γ is static (see Figure 1) through the control process, it effects the transformation equation, and can be set at any value. The orientation angles of the end cluster which are required for keeping fixed orientation under end point control will be developed later.

The numerical procedure of transformation can be outlined as shown by the flow chart in Figure 6.6-2.

(1) The program reads in the angular position Vector $\bar{\theta}$ and computes the Jacobian matrix (for the region of its position).

(2) The program inverts the matrix to obtain $J^{-1}(\theta_1)$.

(3) The input control vector $\hat{\bar{X}}_1$ is read and is multiplied by the inverted Jacobian matrix $(J^{-1}(\theta_1)\dot{\bar{X}}_1)$.

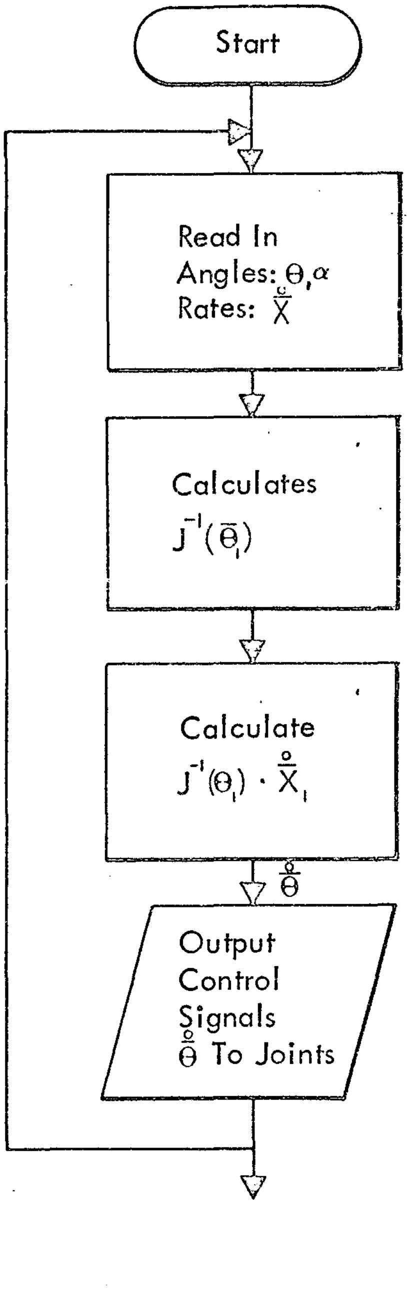


FIGURE 6.6-2
DIRECT COORDINATE TRANSFORMATION
FLOW CHART

0142-10054

(4) The result is an angular rate Vector ($\dot{\overline{\theta}}_1$) which is fed as a control rate to the boom joint motor.

(5) The process repeats itself recursively throughout the control process.

The time cycle at which angle rates are calculated determines the smoothness of the control signals. By using a computer stored table of trigonometric functions the computation time can be reduced considerably. A computation cycle time of less than 50 msec is feasible. This speed can provide over 20 computational cycles per second which is more than sufficient to produce a smooth movement.

6.6.2.3 Numerical Transformation

The direct transformation technique can't be used for mapping three Euclidian input rates into four joint angle rates since the inverse Jacobian matrix is not defined when the vector components of $\overline{\theta}$ exceeds those of $\overline{X}$. The numerical transformation technique can be developed as follows:

Assume that the arm is at a position $\overline{\theta}$ and an input command $\overline{X}$, is applied. From equation (2) $\Delta\overline{X}$, can be written as

$$\Delta\overline{X}, = J(\overline{\theta}) \circ \Delta\,\overline{\theta}, \tag{6}$$

where $\Delta\overline{X} = (\Delta X, \Delta Y, \Delta Z)$, $\Delta\,\overline{\theta} = (\Delta\alpha, \Delta\beta, \Delta\gamma, \Delta\varphi)$. Given $\overline{X}$, and $J(\theta_1)$ it is possible to solve equation (6) numerically by testing all values of $\overline{\theta}_1$, that is all combinations of $(\Delta\alpha, \Delta\beta, \Delta\gamma, \Delta\varphi)$ until a solution is obtained. Since such calculation will require enormous amounts of iterations only three values of $\Delta\overline{\theta}$, will be tested.

$$\Delta\overline{\theta}_1 = 0, \pm 1^{\circ}$$

This approach is based on the assumption that motions are continuous in $\overline{\theta}_{1,}$ (Apple and Reswick, 1970). The computer must perform

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Apple, H.P. and Reswick, J.B. "A Multi level approach to orthotic/prosthetic control system design" Proceedings of Third International Symposium on External Control of Human Extremities, Dubrovnik, August, 1969.

only 81 iterations per joint. Since there is not a unique solution to equation (6) different values of θ can provide a solution - a selection criteria must be employed in determining the specific $\overline{\theta}$.

Accordingly it is proposed to select the moves which minimize:

$$\left|XD-X\right| + \left|YD-Y\right| + \left|ZD-Z\right|$$

XD, YD, and ZD are the inferred future positions and can be predicted as follows:

$$XD = X_1 + \Delta X \cdot K$$
$$YD = Y_1 + \Delta Y \cdot K$$
$$ZD = Z_1 + \Delta Y \cdot K$$

X_1, Y_1, and Z_1 and $\alpha, \beta, \gamma, \varphi$ must be kept within upper and lower limits. Figure 6.6-3 describes the flow chart for the algorithm. This algorithm has been termed the "Eighty-One" algorithm and has been developed at Case Western Reserve University. Using the criteria proposed here, the computation cycle of the program will be 40 sec. Changing the criteria to a minimum distance (sum of squares) will increase the computation cycle to 100 msec.

6.6.2.4 Techniques Tradeoff

Both the direct computation and the numerical techniques fit the application at hand. The numerical transformation is advantageous since it offers end point control with 4 degrees of freedom. However, its accuracy is lower and is a more complicated program.

6.6.2.5 Motion Coupling

The orientation of the links of the end cluster of the boom can be kept at a fixed relative position to the coordinate axis while the Boom is in motion. The operator can set up a preferred orientation in the angles δ, η and μ and keep this orientation regardless of the state of α, β, γ and φ (see Figure 6.6-1).

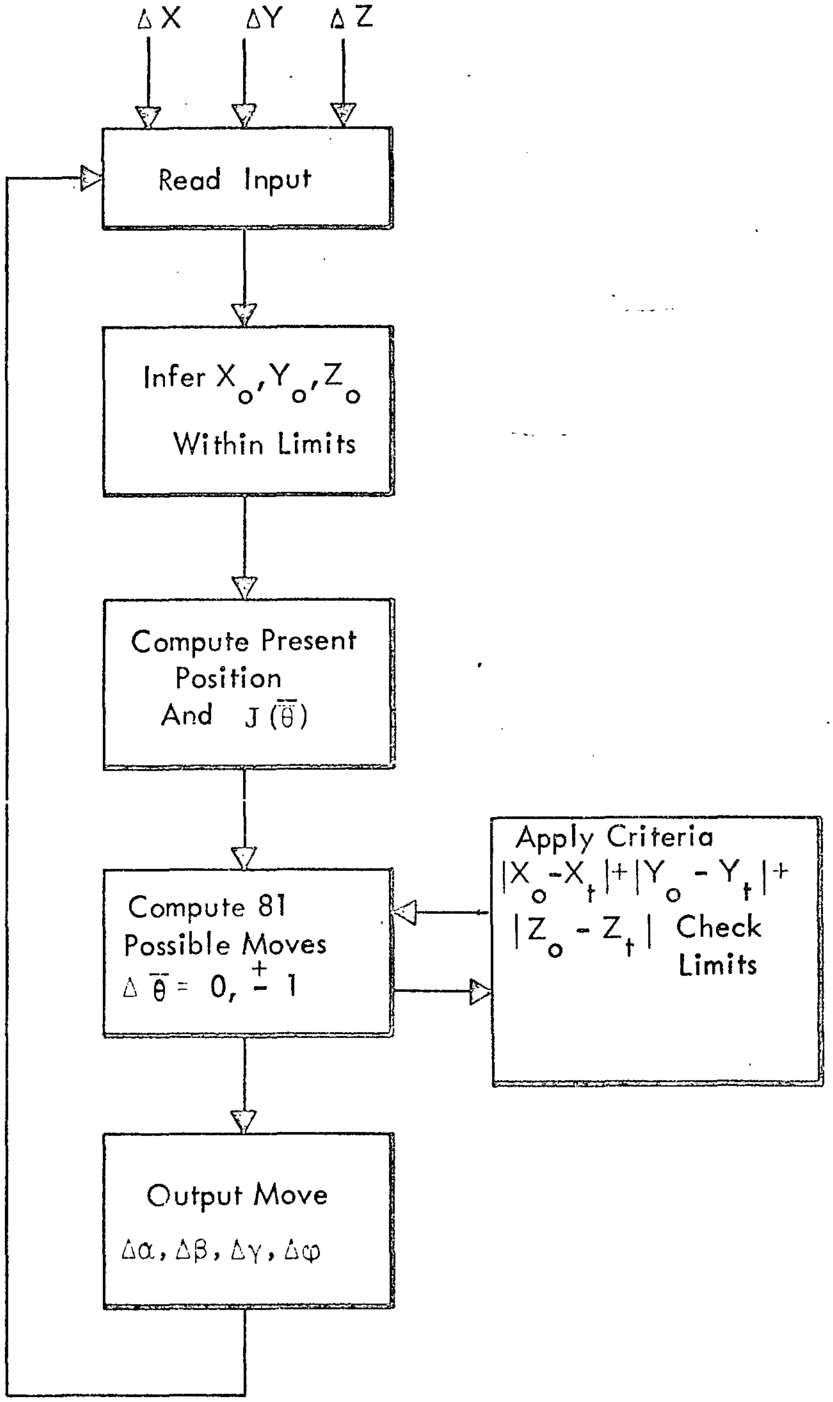

FIGURE 6.6-3
"EIGHTY-ONE"
END POINT CONTROL PROGRAM

This can be performed as follows:

The position of the end point of the end cluster at any time with respect to the coordinates axis is $\overline{\Omega}$ where $\overline{\Omega} = [\delta, \Omega, \mu]$

where $\delta = \alpha + \beta + \delta_1$, $\Omega = \varphi + \Omega_1$, and $\mu = \gamma + \mu_1$

δ_1, Ω_1 and μ_1 are the angles which set up the orientation of the End Cluster with respect to the position of the Boom.

In order to keep δ and Ω constant when α, β, φ and γ change, an amount equal to the change is added to each. Thus, for constant orientation, the values of δ, Ω and μ will be:

$$\delta = \alpha_o + \beta_o + \delta_1 + \int_o^t \dot{\alpha}\, dt + \int_o^t \dot{\beta}\, dt$$

$$\Omega = \varphi_o + \Omega_1 + \int_o^t \dot{\varphi}\, dt$$

$$\mu = \gamma_o + \mu_1 + \int_o^t \dot{\gamma}\, dt$$

where α_o, γ_o and φ_o are the initial angles at which the orientation was set up.

6.6.3 Supervisory Control

6.6.3.1 Program Concept

The basic functions of the control system are defined by a set of computational modules. Figure 6.6-4 illustrates the interaction between the modules and how they are organized into a functional system. A description of each of the computational modules is given below:

(1) Task List Generator

This module reads in the signals which describe the movement of the boom and generates the specific control functions. Trajectories which are generated by a small boom model are smoothed and checked for potential collisions with obstacles. If such collisions are detected, the trajectories are modified for obstacle avoidance. After this operation the Task List Generator organizes the data points of the trajectory of each of the boom joints into an expanded time scale. This is performed by a

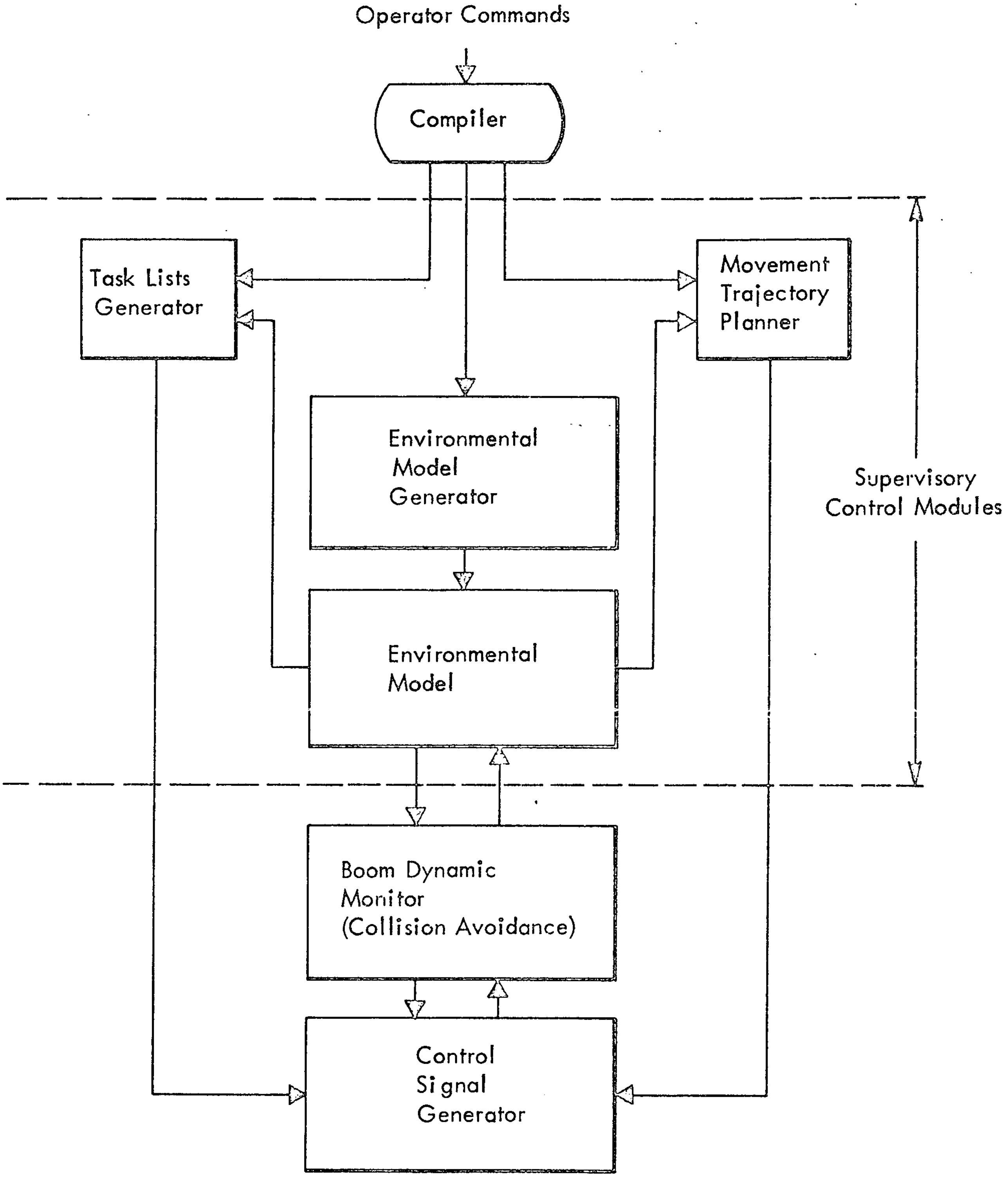

FIGURE 6.6-4
SUPERVISORY CONTROL PROGRAM

simultaneous interpolation of the data points of each joint.

The expanded-time-scale trajectory is used later to produce a movement of the boom itself at a slower rate. The data points of the expanded trajectory are organized into a list and can be called at a later time by the compiler.

(2) Environmental Model

This program module provides the system with an internal model of the environment of operation. It interacts with the trajectory planning program and the task lists generation program to provide data regarding the existence of obstacles in the path of movement of the boom. It consists of a three-dimensional map of the environment with a simple description of object locations which indicate whether a region is occupied or is free for boom travel.

(3) Environmental Model Generator

This program module consists of a set of subprograms which are capable of constructing and manipulating the computer model of the "real world". The Model Generator keeps track of changes in the operational environment and updates the computer model as they occur. For example, when the space shuttle dock with the space station, the description of the shuttle and its location is entered to the environmental model.

(4) Movement Trajectory Planner

This module accepts command signals from the operator which specify a required location for the boom. The trajectory planner defines a control time function for each of the joints of the boom which would direct the end cluster to the required location. If necessary, the specific trajectory can be (near) optimized with respect to energy expenditure associated with the movement.

The trajectory planner interacts with the environmental model in planning the movement pattern; the path of movement is adjusted so as to avoid collision between the boom and the surface of the space station or the space shuttle.

6.6.3.2 Task List Generator

Figure 6.6-5 describes the flow chart of the task list generator.

The program will accept input signals from each of the joints of a geometrically-similar model of the boom. The signal which describes the movement patterns of the model completing a task is smoothed by the program.

The smoothed control signals are stored as a task list which can be generated by the computer at rates slower than the original input signals. The task lists could be called by the supervisory control program to drive the servo loops of the program.

This will produce a smooth trajectory of movement in the boom geometrically similar to the trajectory induced in the model controller.

The program operates as follows: (See Figure 6.4-5).

(1) The program reads in signal data samples which are generated by the small boom model.

(2) The signals are smoothed by an exponential smoothing algorithm as follows:

$$\tilde{V}_{n+1} = \tilde{V}_n + \alpha (V_{n+1} - \tilde{V}_n)$$

where $\tilde{V}_{n+1}$ is (n + 1)th smoothed data sample at the (n+1)th sampling interval, V_{n+1} is the raw data sample and V_n is the smoothed data sample at the nth interval; α is the smoothing constant and determines the cut-off frequency of the smoothing filter. (A secondary smoothing process can be done)

(3) The program then checks the trajectory to detect a potential collision. If a collision is detected, the trajectory is modified by using the obstacle avoidance program.

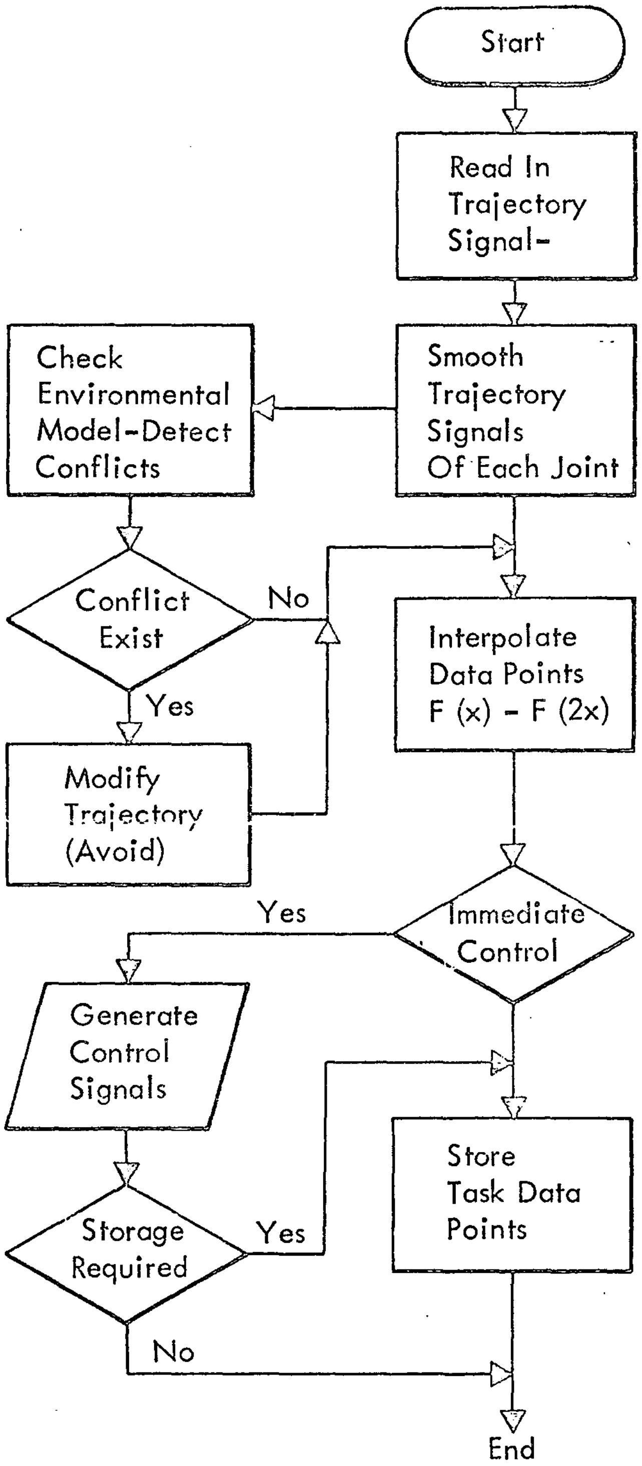

FIGURE 6.6-5
TASK LIST GENERATOR FLOW CHART

(4) The program interpolates the smoothed signal data points to expand the time scale of the signal. The interpolation process employs a second order polynomical curve fitting technique,

i.e., $f(x) = ax^2 + bx + c$

(5) The interpolated data samples are then used either to translate the boom immediately or can be stored on a disc as a task list. The task list can be called at a later time by an operator control command.

6.6.3.3 Environmental Model

6.6.3.3.1 Basic Design

Techniques for computer mapping of the environment of operation for supervisory control were considered by various groups (Whitney, 1967, Pieper 1968, Nillson 1967).

The case at hand is somewhat simpler since supervisory control is restricted to gross translations and does not involve dextrous manipulation. A simplified map of the environment is adequate. Accordingly, an environmental map that describes regions in which the boom and its elbow can travel freely without collision will be used. This map minimizes memory requirements and computation time.

This map can be described as follows:

(1) The operational environment in which the boom moves is divided into a set of subspaces (three dimensional regions) which are subdivided into a set of cells.

(2) The occupational status of each of the subspaces is determined by whether it contains an object or not. Accordingly there are three occupational states: (1) empty subspace, (2) partially filled subspace, and (3) completely filled subspace.

(4) The environment is stored in the computer as a set of lists of subspaces. A list is available for each part where the boom can be located. The list covers all of the boom's reachable space, and will be termed the Port-List.

(5) In scanning the environment the program scans the list of subspaces which lie along the selected path of movement of the boom, end-cluster, and elbow. Information regarding the occupancy of the subspaces is used by the trajectory planning program.

(6) Computer memory is conserved by using the following storage techniques for describing the occupancy of the environment.

    (a) A generalized code for describing the subspace location and its occupancy status.

    (b) Off-line storage for all Port-Lists. Only the list which belongs to the Port to which the boom is attached at a particular time will be called into on-line storage.

6.6.3.3.2 Model Structure and Storage Techniques

The design of the basic elements of the environmental map is given as follows:

(1) Environmental Subspaces

The environment of operation will be divided into a set of 2' x 2' x 2' subspaces. Each subspace will be subdivided into 8 cells of 1' x 1' x 1' each. A partially filled subspace contains some filled cells. A cell is then the smallest distinguishable space that can be examined for object occupancy.

The volume of operation of the boom can be estimated as follows:

> Estimating that the boom can extend to reach a distance of 60', then it will cover a volume defined by a half a sphere whose radius is 60' which is connectected in its base to the base of two half spheres with a radius of 30' each. An illustration of this structure is shown in Figure 6.6-6.

The volume covered by this is 280×10^3 ft^3. The volume will be divided into 35.0×10^3 subspaces of 8 ft.^{3} each.

Port-Lists

The Port List consists of a three-D matrix that describes the occupancy status of each of the subspaces and their location in cartesian coordinates. An element of the matrix is defined as:

Sijk

where S describes the occupational status of the ith subspace and the value of Si, j, k defines the location of the element in space.

The values of S are either 0, 1, or 2.
S = 0 - indicates an empty subspace
Sijk = 1 - indicates a partially filled subspace
Sijk = 2 - indicates a filled subspace

(2) Map Interrogation Technique

The technique by which the environmental map is interrogated is described by the flow chart in Figure 6.6-7 as follows:

(a) The program starts by reading in the location in space for which the occupancy status is checked (X, Y, Z)

(b) A value of the corresponding (i, j, k) is determined. Since (XYZ) is continuous in space and (i, j, k) is discrete, a conversion algorithm which assigns any value of (X, Y, Z)

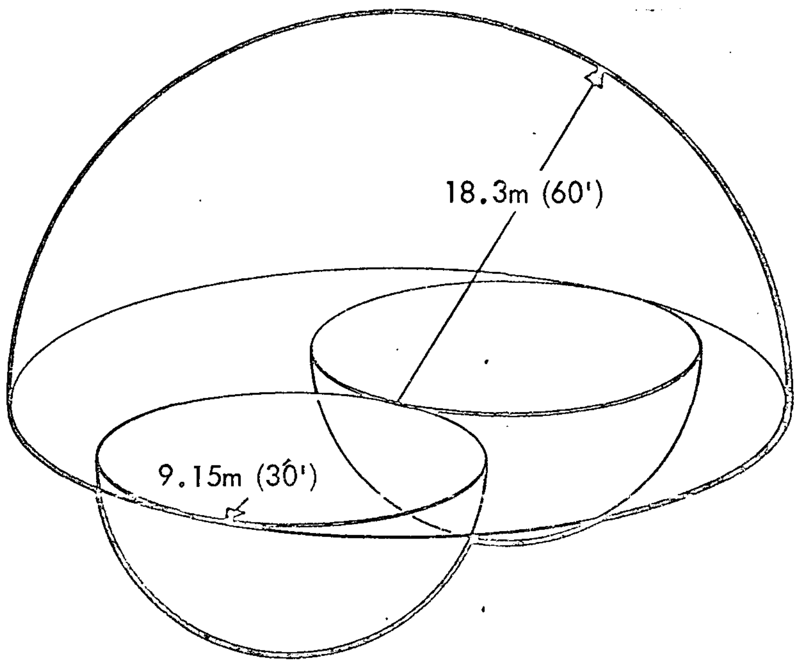

FIGURE 6.6-6.
APPROXIMATE OPERATING VOLUME OF THE MANIPULATOR BOOM

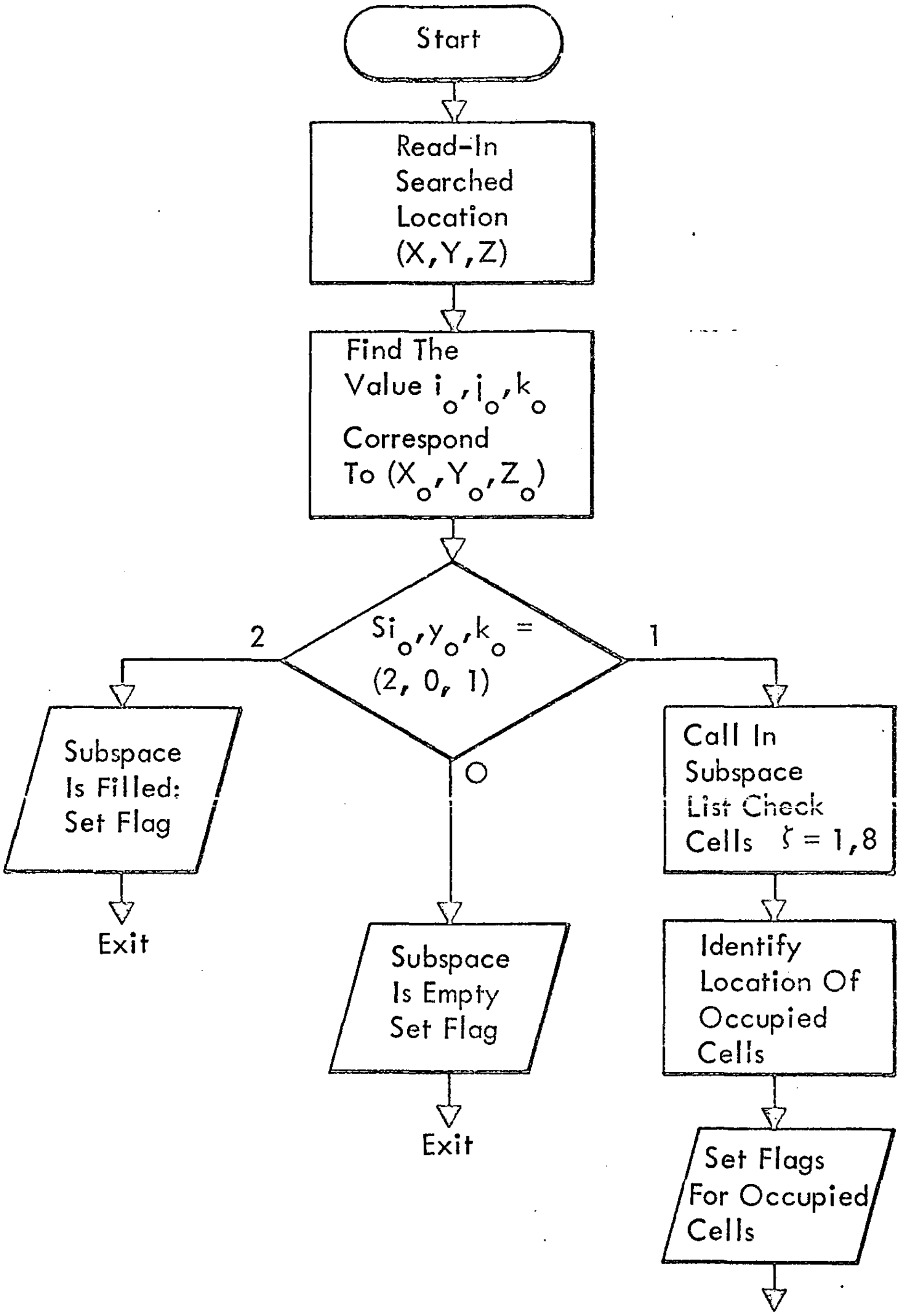

FIGURE 6.6-7
ENVIRONMENTAL MAP INTERROGATION PROGRAM

to (i, j, k) is used. This algorithm consists of the fixed point division of the value of X, Y, and Z by the selected length of the subspace edge, and the addition of half the length of the edge, for the subspace of 2' x 2' x 2'. The values of i, j, k will be determined by:

$$i = x/2 + 1, \ j = y/2 + 1, \ k = Z/2 + 1$$

(c) Following the findings of (i, j, k) the program reads in the value of Sijk and examines whether the subspace is filled, partially filled, or empty. If it is filled or empty, a flag which indicates this status is generated.

(d) If the subspace is partially filled, the cells list ($C = c_1, c_2 \ldots c_8$) is checked for occupational status. The list C is stored in another memory location and is identified according to the value of (i, j, k). The list elements C_i can take a value of 1 or 0 where 1 indicates a filled state and 0 indicates an empty start.

(e) The program then identifies the location of the occupied cells and sets flags for obstacle locations.

(3) Map Storage Scheme

There will be approximately 35,000 8 foot square subspaces in each Port List. To define the occupational status of each subspace, 2 bits will be required. Since there are 32 bits in each word of each word memory, the total memory requirements will be 2,190 words of core.

All the partially filled subspaces will be grouped into a Cell-List. For each partially filled list, C, 8 bits will be required. The amount of storage required to store Cell-Lists at any time will vary with number of partially filled subspaces. For estimation purposes, let's assume that a quarter of the subspaces are partially filled. Then the required memory storage will be: (1/4 x 35,000) 8/32 = 2190 words.

The total memory requirements will be the sum of the fixed subspace requirement and the floating level of occupied subspaces. For the two cases considered here, there will be 4,180 K of core.

6.6.3.4 Environmental Model Generator

Figure 6.6-8 describes operation of the Environmental Model Generator. Starting at the top, the functions of the program can be outlined as follows:

(1) The program reads in a mapping command, which can be of two forms: (1) A list mapping command: or (2) a point mapping command. The first command form introduces to the environmental model a sequence of occupational changes in a specific subspace. The second command form introduces to the environmental model a set of changes which describes a complete object. This set effects the occupational status of a number of subspaces. It is used to introduce space station modules as growth of the station occurs. A map list can be also used to describe the shape of the space shuttle when it docks with the space station.

(2) For list mapping the program calls in the required list from a peripheral storage device (tape) to core memory.

(3) The coordinates at which the center of the object is located in the operational environment are read and the program determines the corresponding discrete subspaces which the object will occupy. This involves the determination of the value of the set (Sijk).

(4) The program then updates the Port-List Matrix by substituting the new values of S in each of the subspaces that the object occupies. If they are partially filled subspaces, the program constructs a set of Cell-Lists to describe the occupational status of each partially filled subspace.

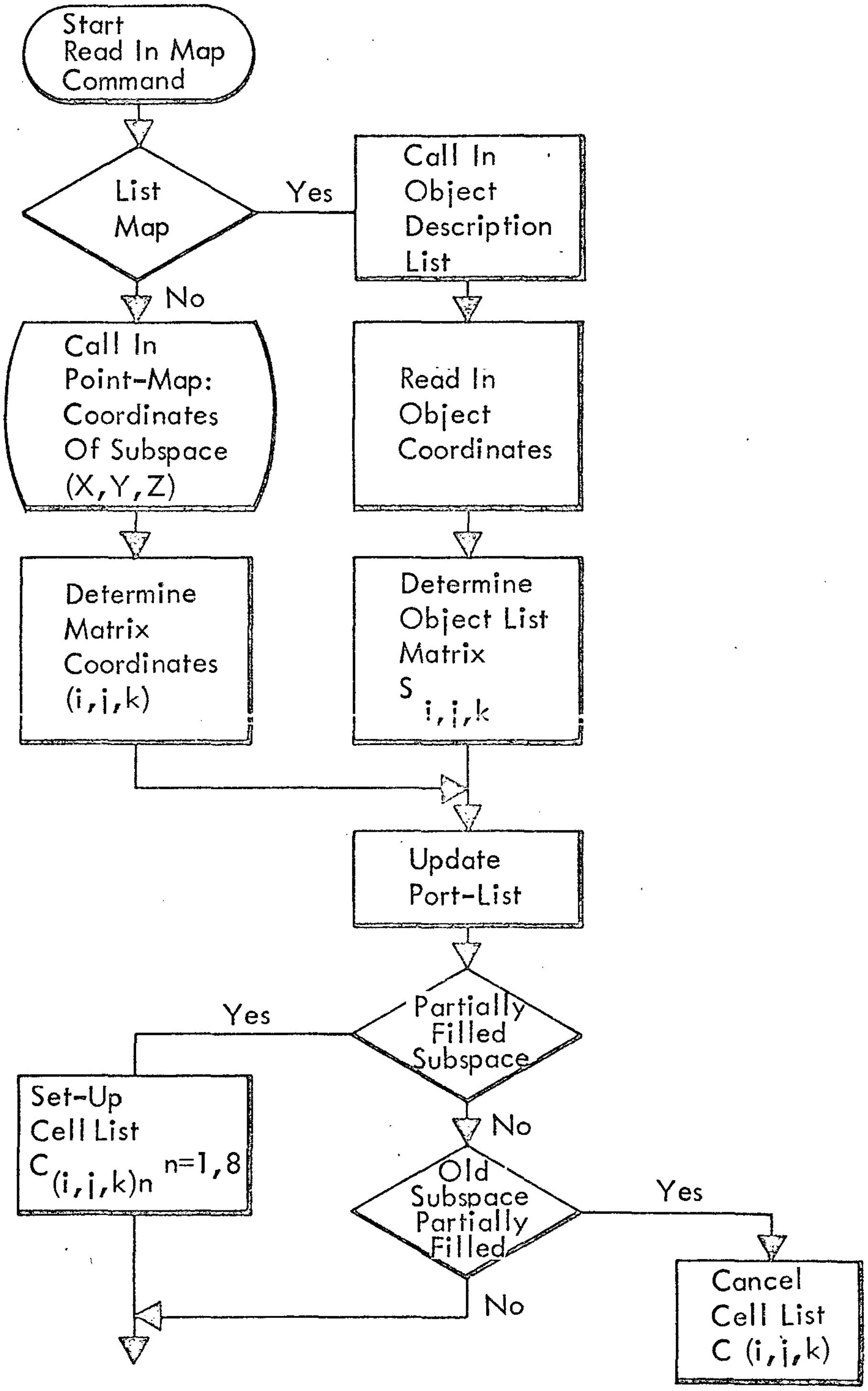

FIGURE 6.6-8
ENVIRONMENTAL MODEL GENERATOR FUNCTIONAL FLOW DIAGRAM

(5) Starting back at top, when the mapping is not a list map, the program transfers operation to point mapping where the coordinates of the subspace to be mapped are read. The values of i, j, k which corresponds to the coordinates of X, Y, Z are determined.

(6) If the list is partially filled, a flag is set in the Port-List, and the Cell-List is constructed to describe the specific occupational status of the subspace.

(7) If the subspace is not partially filled, the program updates the Port-List Matrix. If the subspace is partially filled, the program constructs the Cell-Lists.

(8) If a particular updated subspace is not partially filled at the nth updating cycle, the program checks whether it had a partially filled status before the current Port-List Updating at the (n-1)th updating cycle. If so, the program cancels the Cell-List associated with the particular subspace.

6.6.3.5 Movement Trajectory Generator

Figure 6.6-9 describes the operation of the trajectory generation program. The program reads in the present and desired position of the end point of the boom Xp and $\overline{X}$d and the corresponding angle values which define the orientation of the elbow γp and γd. Following this, the program generates a movement trajectory as follows:

(1) The program determines the equation for a straight line connecting Xd and Xp. The criteria for determining the trajectory of end point movement in an obstacle-free environment is to minimize the distance travelled by the end point.

(2) The program then identifies the subspaces i, j, k through which the end point will travel to determine whether any obstacles exist. If obstacles exist the program calls an AVOID subroutine which computes a new trajectory.

(3) If no obstacles exist the program continues to examine whether there are any obstacles in the path of the large load. Large loads occupy a trajectile volume which differs from the end point trajectory.

(4) The program continues to follow similar trajectory checks for the boom's elbow and the boom's link. Each time an obstacle is detected the AVOID subroutine is called.

(5) After completing all obstacle checks, the program generates the straight line trajectory for the end-point.

The equations for generating the angular displacements at each joint of the boom can be specified as follows:

The position of the end point vector ($\overline{X} = [X, Y, Z]$) at any time is given as a function of the joint angles vector $\overline{\theta}$ such that:

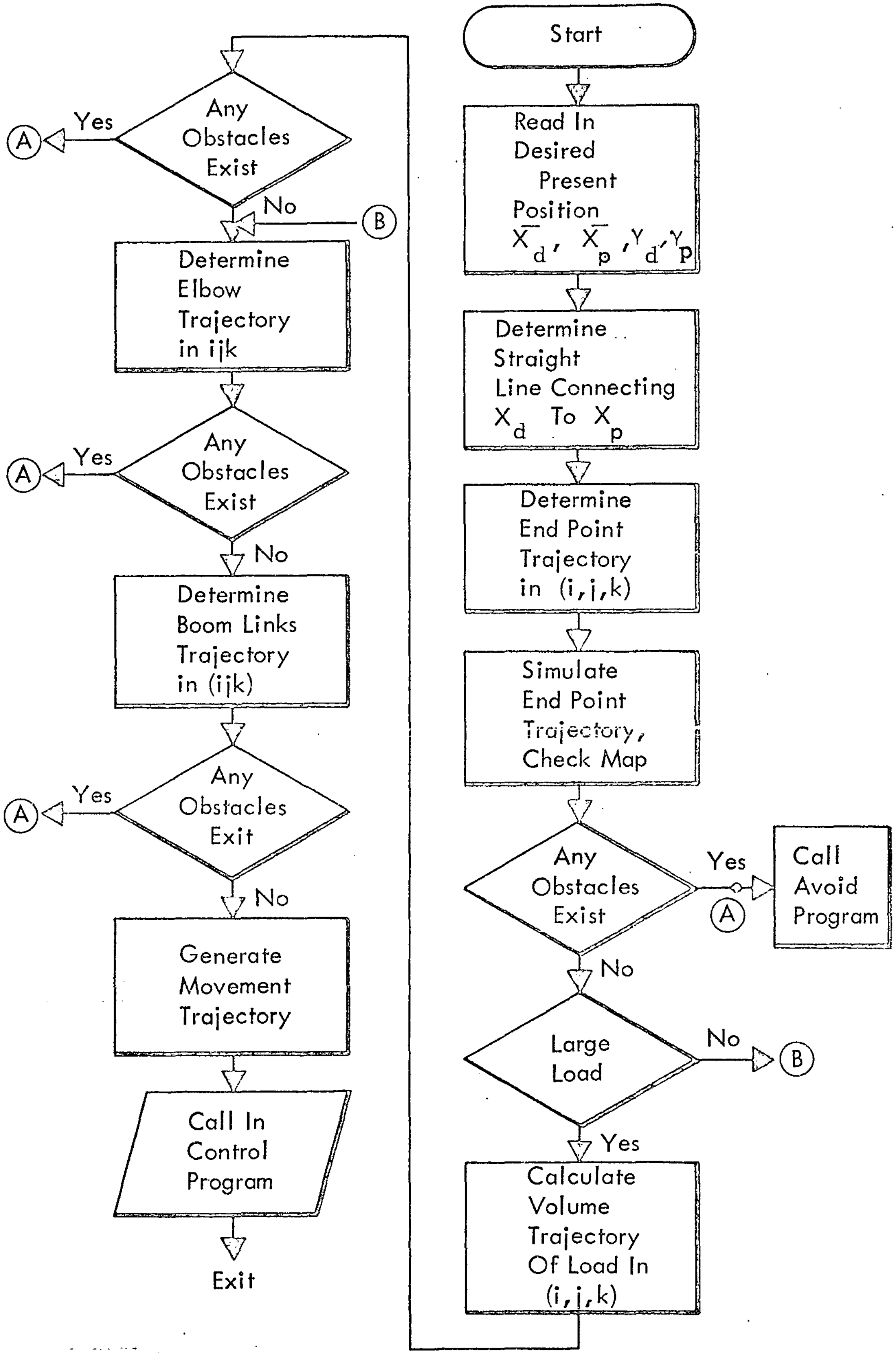

FIGURE 6.6-9
TRAJECTORY GENERATION PROGRAM FLOW CHART

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$$\overline{X} = f(\theta) \tag{1}$$

$f(\theta)$ is shown in expanded form equation (5) Section 6.6.2.1.

6.6.3.6 Obstacle Avoidance

The obstacle avoidance program consists of the AVOID and the TRAJL routine. The AVOID program is called in as obstacles are encountered by the boom end point, the elbow or its link. The program given here was proposed by Pieper (1968).* It is applied here to modify the initial minimum distance strategy to an obstacle avoidance strategy. The program modified the trajectory of movement on the basis of geometric conditions around the area of conflict.

Although Pieper's program uses more specific environmental mapping techniques, the obstacle avoidance program could be easily used with the environmental model available here. Figure 6.6-10 shows the flow chart of the AVOID subroutine as applied to the system at hand.

An additional program termed TRAJL is employed. This program changes the basic control strategies in the case of (1) conflict with few objects (2) physical limits on the joint movements (3) unproductive outputs of the AVOID program.

The input to the TRAJL are two sets of joint angles the initial position and the final position. The output of the program is an array of angles specifying intermediate positions. An increment specifying the desired movement between intermediate positions is specified.

The strategies which are provided by the program can be described as follows:

(1) Each angle is incremented toward the final goal.

(2) Computation of two intermediate positions to move the manipulator over a set of obstacles.

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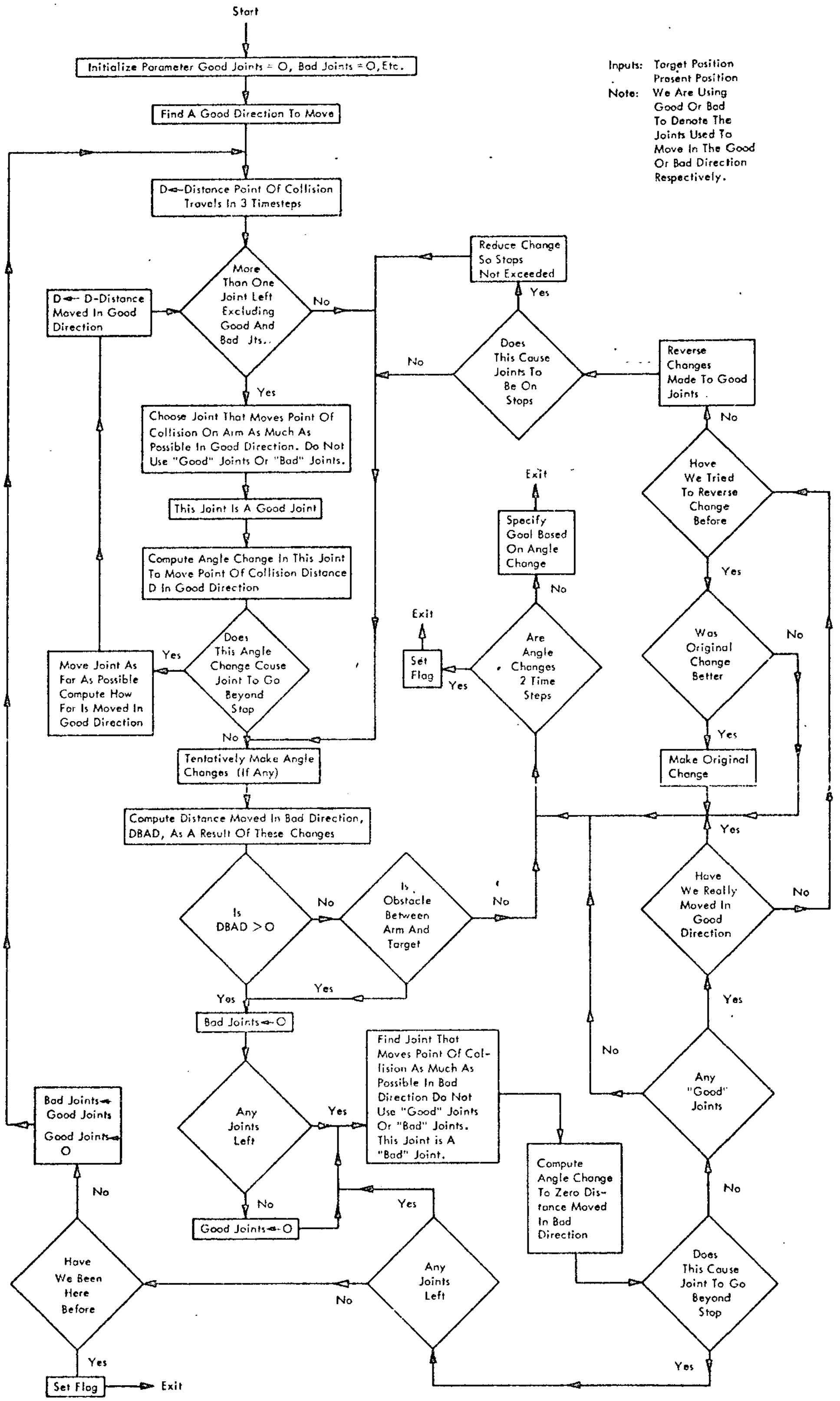
*Pieper, D. L., "The Kinematics of Manipulators Under Computer Control", Ph. D. Dissertation, Stanford University, 1968.



Inputs: Target Position
Present Position

Note: We Are Using Good Or Bad To Denote The Joints Used To Move In The Good Or Bad Direction Respectively.

FIGURE 6.6-10
BLOCK DIAGRAM OF AVOID

(3) Folding of the manipulator and shortening it and move it in front of any obstacle.

A flow chart of the program is shown in Figure 6.6-11. The program normally starts by applying the first strategy. If it fails it moves to the second strategy. If conflict is predicted in pursuing the second strategy the AVOID program is used. If the strategy fails the third and the fourth strategy is used. If a trajectory then is not produced the program halts. More details regarding the program are available in Pieper's (1970) work on the Kinematics of Manipulators Under Computer Control. It should be noted that the AVOID and TRAJL programs were designed for general purpose manipulation. In fitting these programs to the present application various simplifications can be made which will reduce the amount of memory required.

6.6.3.7 Computer Command Language

The operator will control the computer with a high level command language through an alpha-numeric keyboard.

The command language to be used falls into the category of a computer compiler language. The language must be quickly communicable and be interpreted unabiguously by the computer.

Extensive work has been performed by various groups in designing such command languages for remote manipulation. Among them is the MANTRAN compiler which was designed at M.I.T. (Barber, 1967).* The ARM language of SRI (Hill and Bliss, 1971).*

These languages were designed for general purpose manipulation and thus are more complex than the task requirements at hand. However, some of the syntax and the experimental work of these groups can be used in the detailed design phase for adapting a command language for the boom control system.

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*Hill, J. W., Bliss, J. C., "Tactile Perception Studies Related to Teleoperator Systems", NASA, June 1971, Contract NAS2-5409.

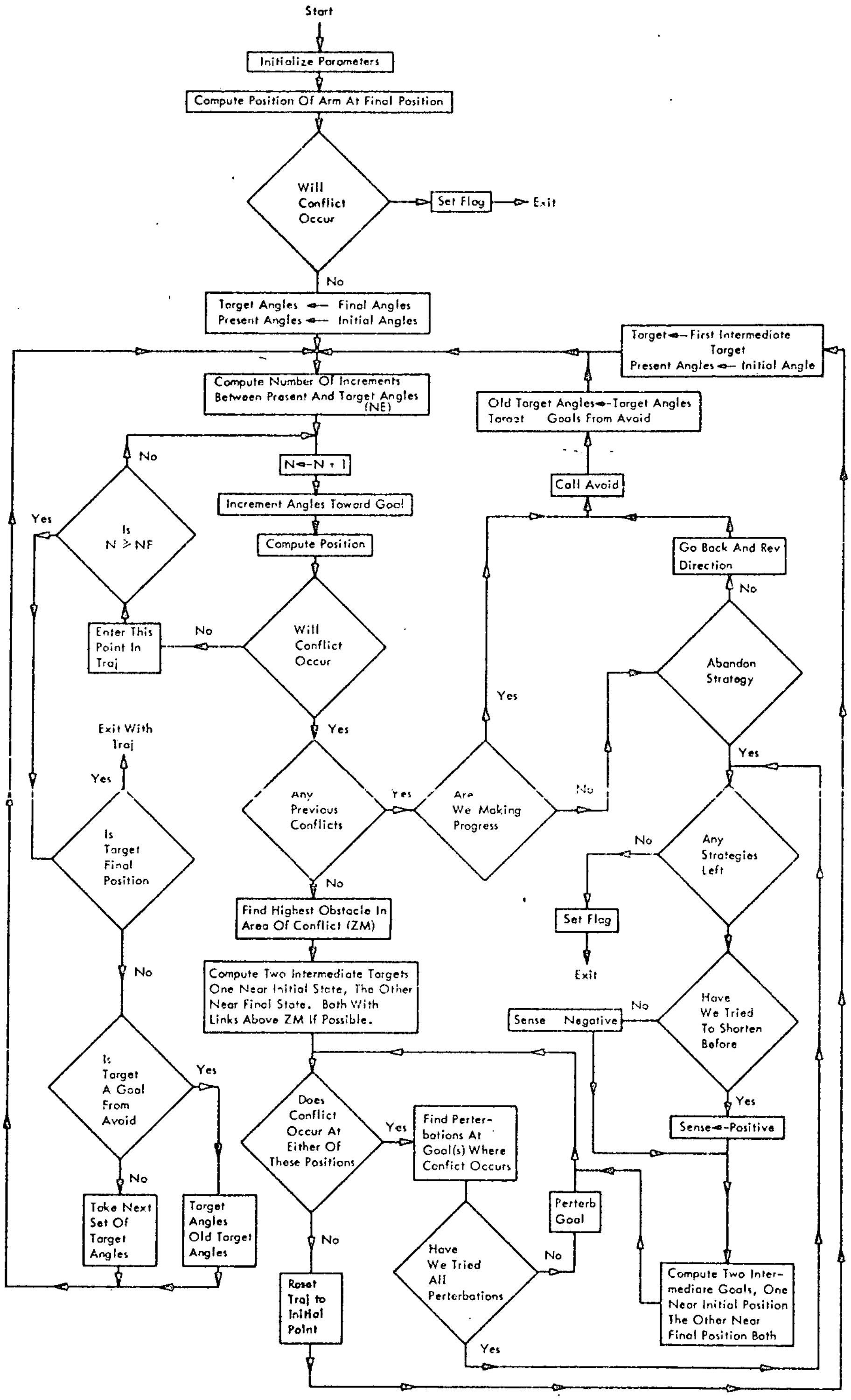


FIGURE 6.6-11
FLOW CHART BLOCK DIAGRAM OF TRLTRJ

The major criteria in establishing the command language is to minimize the number of symbols and to provide an easy "formula" for arrangements of the command symbols in a meaningful command string. This can be done by establishing direct compatibility between the command symbol and the specific subgoals they represent.

An example for a command string can be given as follows:

(1) Command string (GO TO LOC α)

(2) The command string consists of three words: GO, LOC, and α which implies GO TO LOCATION α. This command could also include a set of ordered locations to which the boom is instructed to move sequentially.

(3) Other types of general commands which were developed by Barber are as follows:

MOVE RIGHT, α, β, STOP.

The arm end point moves α point right until the letter β is typed which provides the instruction of stopping. At the detailed design phase a specific command language is to be designed. The language should be based on detail examination of the task requirement. An optimum set of symbols and command strings is to be established. The selection process should be supported by a brief experimental evaluation study which will test operator's capability to remember the symbols and construct command strings in the operational environment.

6.6.4 Dynamic Monitor

6.6.4.1 Program Concept

The flow chart of the dynamic monitor is shown in Figure 6.6-12. The operation of the program can be explained as follows:

(1) The program reads in the position of the end point and the elbow and calculates the instantaneous velocity of the end point and the elbow. A potential collision is then detected using the following algorithm:

(2) Given $\overline{X}_p$ and $\dot{\overline{X}}$, if the boom end point continues to move in the same direction, its position after a time interval of t will be:

$$\overline{X}_t = \overline{X}_p + \dot{\overline{X}} \; \Delta t$$

(3) Given $\overline{Q}_p$ and $\dot{\overline{Q}}$ and applying the same equation to the elbow,

$$\overline{Q}_t = \overline{Q}_p + \overline{Q} \; \Delta t$$

Since $\dot{\overline{X}}$ and $\dot{\overline{Q}}$ defines a specific direction, it is possible to estimate the future position of the end point and the elbow at a time Δt ahead.

6.6.4.2 Implementation

Figure 6.6-12 illustrates the flow chart of the program. Using the value $\overline{X}_t$ and $\overline{Q}_t$, the program interrogates the environmental model and checks whether an obstacle exists in the coarse movement of the end point and the elbow.

(1) From the predicted position of the elbow and the end point, the program detects whether the links of the boom are on a collision couple. The locations of points along the connected links of the boom at 2 ft. apart are predicted and examined. This location is determined by:

Performing a geometrical projection of the link on the X, Y, and Z axes. Similar projection is performed with the free link of the boom to determine its predictive course of movement.

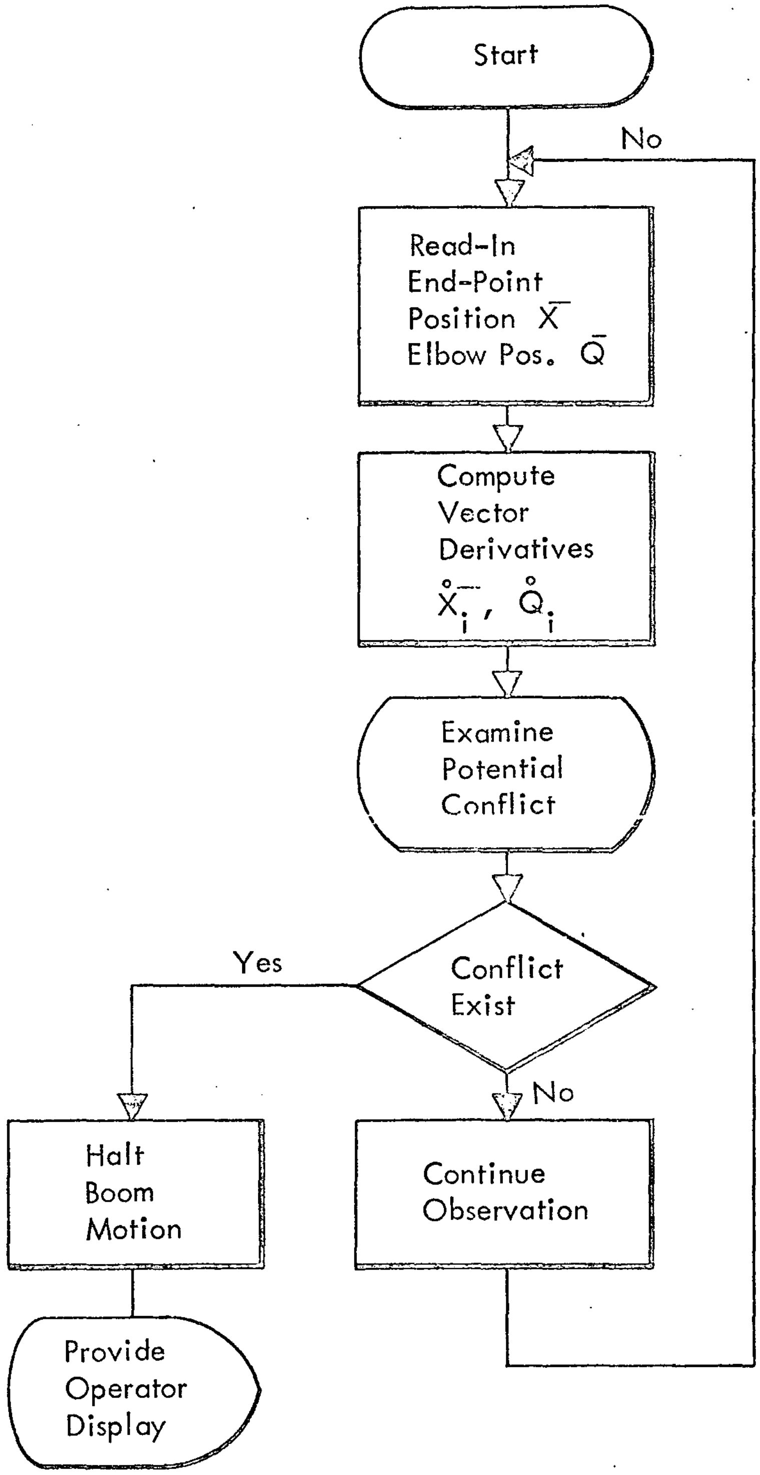


FIGURE 6.6-12
DYNAMIC MONITOR PROGRAM FLOW CHART

(2) If an obstacle is predicted the program halts the motion of the boom and sends a warning signal to the operator.

A critical consideration in the design of the Dynamic Monitor is the length of time in the future Δt, for which the position of the boom is predicted. This time must be long enough in order to allow for the boom control system to halt the motion. The Δt should be adjusted according to the mass of the load carried and the capacity of the control system to absorb the kinetic energy of the boom and its load.

6.6.5 Hardware Considerations

6.6.5.1 System Overview

The integrated control system is illustrated in Figure 6.6-13. The system consists of three main subsystems. These are (1) the boom control loops, (2) the computer subsystem, and (3) the operator control station.

An on-line interface subsystem connects the computer to the boom control system. This includes the analog to digital and digital to analog conversion system which is part of the on-line interface subsystem. The boom is controlled by the computer by either a position mode or rate control. Under supervisory control,position control is used. Rate control is used in the end point control mode.

Feedback information from the boom is fed both to the computer as an input to dynamic monitor program and to the servo loop as position feedback.

The computer utilizes a mass storage device to store the task lists and the map of the operational environment in the form of port lists.

The hardware required to support the operation of the system must include capability for on-line real-time operation, and either on a dedicated basis or a time-share basis.

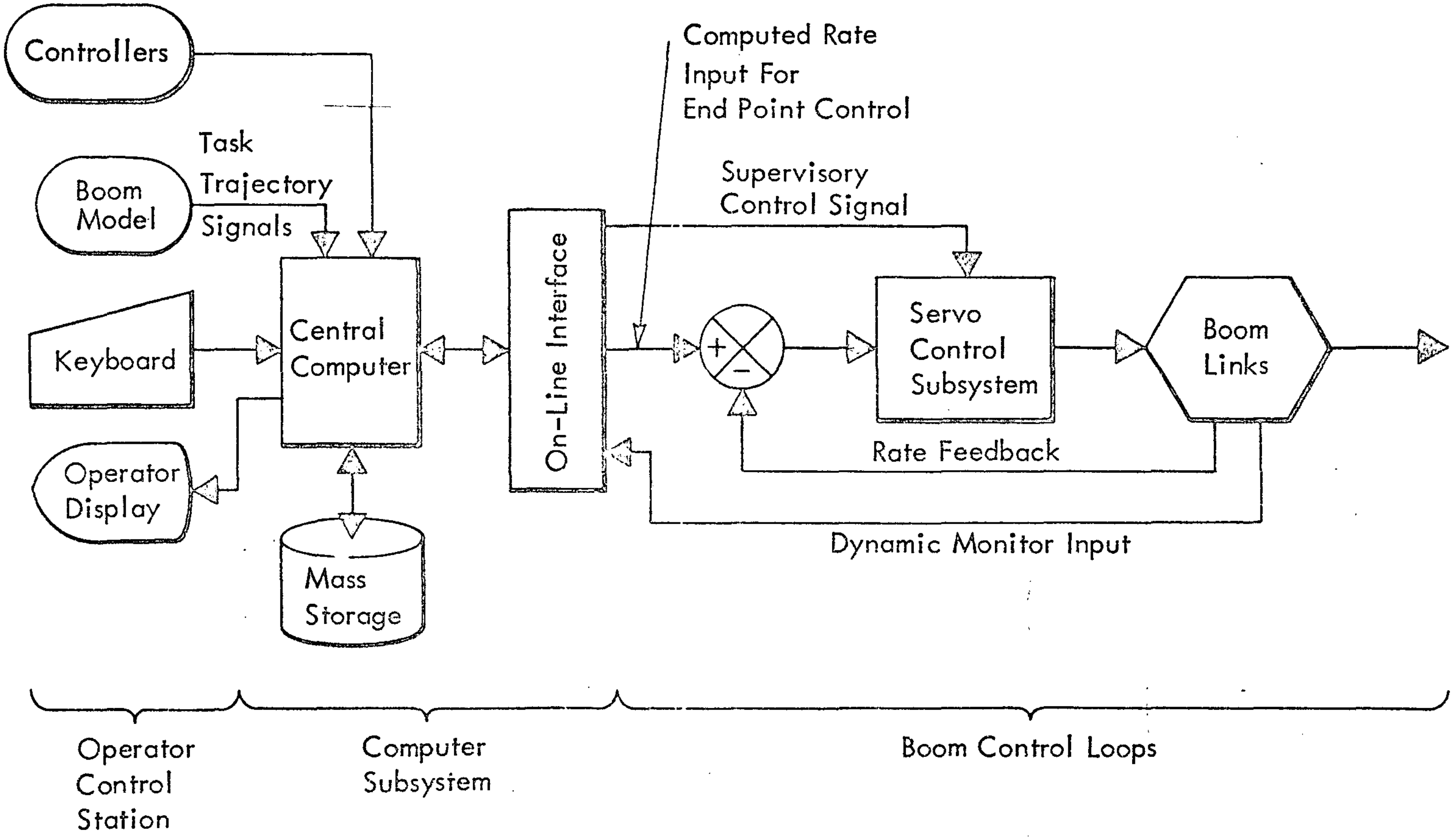


FIGURE 6.6-13
THE INTERGRATED COMPUTER CONTROL SYSTEM

6.6.5.2 Computer Requirements and Time Sharing Availability

The following discussions on computer availability are limited primarily to the space station since complete shuttle information was not available during the present study. Review of the North American Design for the Data Processing Assembly (DPA) of the Space Station revealed that time-shared operation for computer-assisted manipulation is feasible. This conclusion is based on available computer memory as well as computational speeds.

A constraint is imposed on real-time computer availability during the initial phases of the Space Station assembly - up to the completion of the third launching. At this phase the main DPA will not be fully operational. The computational needs of the space station will be supplied by a dedicated computer. However it would be possible to use the space shuttle computer for running the manipulator control programs, with some additional memory.

A viable alternative would be limited use of the control repetoire while the manipulator is controlled from the shuttle. In this control mode supervisory control would operate only with prestored routines covering the sequence of tasks required to unload the shuttle and move cargo to the space station.

While manipulation tasks are performed the primary computer normally operates under reduced load, and thus could be used to process the manipulation programs.

Available computer capabilities are summarized as follows:

(1) Up to 30K of computer core memory will be available between the end of the third launch and the end of the sixth launch.

(2) Allowed computational capacity will be on the order of 500 additions/second.

(3) After the sixth launch 60K of core memory could be made available to the manipulator programs.

Table 6.6-1 summarizes program design requirements for computer hardware and response time. As shown, the above capabilities exceed the minimum required for the support of the manipulator control programs.

6.6.5.3 Interface and Data Transfer

The general interface system which is specified for the space station central computer could also be utilized by the manipulator control programs. This interface consists of a Remote Acquisition and Control Unit (RACU), containing a multiplexer and an analog-to-digital converter. A single RACU interface unit will be available at each of the modules of the space station, in the core module and in the power module.

Control signals to the manipulators will be generated by the RACU and converted to analog signals by a dedicated D/Z subsystem which will be part of the manipulator control package.

Loading of the digital data buss line by manipulator feedback data will be less than 10K bits/second. This load is quite low and is well within the available range.

6.6.6 Electronic Control System

The boom electronic control system is a conventional rate controlled actuator system complicated by computer control, discontinuous data transmission and unconventional loads on the motors. A functional block diagram of the system is shown in Figure 6.6-14. The actuator control shown is typical of actuators in the main boom, auxiliary viewing boom and dexterous end effector.

6.6.6.1 Overall Description

The operator originates signals for the commands by moving the control station controls or by direct input to the computer for a stored routine. The computer smooths the commands and the commands for all actuators are time shared, coded and transmitted on the digital data bus. At the actuator end of the data bus on the boom, the commands are decoded and stored in a buffer register. The command is converted to analog

PROGRAM FUNCTION	OPERATIONAL MEMORY	OFF-LINE STORAGE	REQUIRED RESPONSE TIME
Environmental Model Storage	10 k	150 k	Not Applicable
Supervisory Control Program	8 k	60 k	1 sec.
End Point Control Program	8 k	0	50 m sec.
Dynamic Monitor	2 k	0	100 m sec.

TABLE 6.6-1
COMPUTER HARDWARE REQUIREMENTS
FOR THE BOOM CONTROL SYSTEM

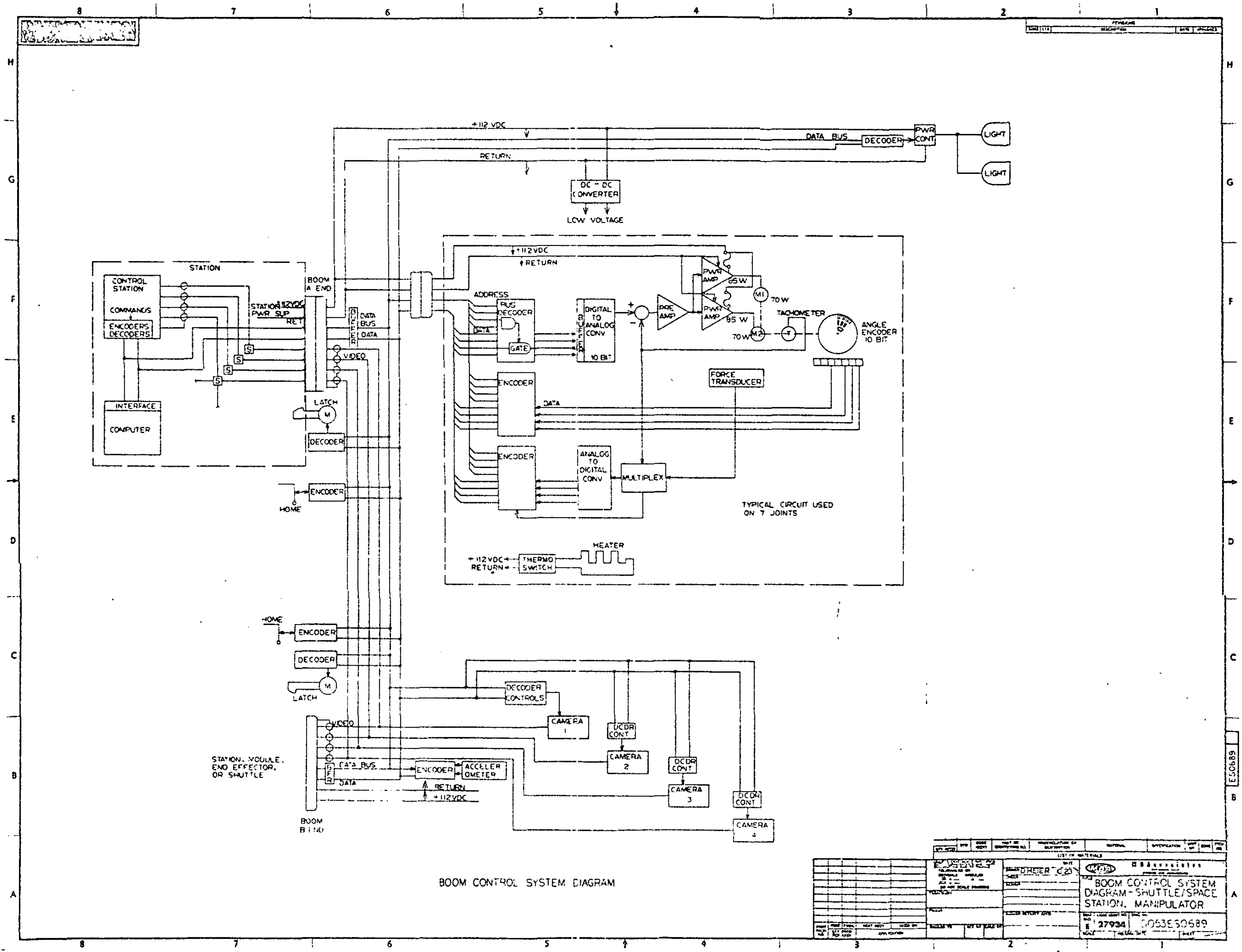


FIGURE 6.6-14
ELECTRONIC CONTROL SYSTEM FUNCTIONAL BLOCK DIAGRAM

voltage by a digital to analog converter and applied to a pre-amplifier. The pre-amplifier forms a pulse width modulated signal from the analog signal. The pulse width is proportional to the amplitude of the analog signal and the pulse amplitude is constant. The pre-amplifier signal is applied to the power amplifiers causing them to switch on and off as driven by the pulse width modulated pre-amplifier. The pulse rate is fast enough (100 Hz) that the actuator cannot respond to the individual pulse, and therefore responds to the average signal. The power amplifiers are much more efficient in this mode. The output stages of the power amplifiers would be four transistors in a bridge connection to drive the motor in both directions from the unipolar power supply. The power transistors would have to be rated at several hundred volts V_{CEO} (voltage from collector to emitter with base biased off) 1 ampere maximum collector current when operating in pulse mode, and approximately 20 watts dissipation in a heat sink. The actuator will incorporate a small instrument tachometer for feedback to insure a linear, proportional rate controlled actuator. The power amplifiers drive dual electric motors which drive a common gear train to the joint. The dual power amplifiers and motors are for redundancy and reliability. If a motor or power amplifier fails open electrically, which is most likely, the other amplifier will drive the other motor at half power. If a motor or amplifier fails short the fuze will remove it from the line and the actuator will operate at half power on the other motor. Digital shaft angle encoders will be used to measure joint angle precisely (10 bit). Their output is fed back to the manipulator computer and shuttle (during station/shuttle capture) by way of the digital data bus. The computer can calculate tip positions and rates from the fixed boom parameters (length) and the joint angles.

6.6.6.2 Boom End Control Transfer

The process of "walking" the boom around the station or from the shuttle to the station requires a sequence of operations for safety and reliable performance. The boom is assumed connected at end B with an end effector on end A when a decision is made to transfer to another root point. If an end effector is attached (see Section 6.10) "System Utility Analysis", the operator moves the end effector to the tool storage point, docks the tool on the twist-lock and releases the boom from the end effector. The boom tip (end A) is withdrawn from the end effector root and moved to the desired root point. End A is inserted in the root point and the latch is actuated. The latch secures the boom mechanically and makes up the electrical connector carrying power and control signals to the boom. A limit switch detects the "home" position of the latch and a set of contacts on the connector indicates a made-up connector. The operator then switches a switch on the control panel to change control of the boom from end B to end A. The computer then checks the latch limit switch for the "home" position and the connector for "made-up", switches the TV video routing to the new root point and readdresses the boom actuators (see Figure 6.6-15). The computer then enables an unlatch operation on end B. The operator then unlatches end B and withdraws the end from the original root point. The operator then latches to an end effector from the storage rack and resumes operation.

In the emergency operation mode without the computer, all switch operations are manual. The end effector is removed as before, the free end A is inserted in the root point and the switch to latch the end in the root point is actuated manually. The panel is checked for a light to indicate the "home" position. The transfer switch on the panel is manually operated to switch the addressing of the actuators from shoulder to wrist and vise-versa. The video has to be rerouted by manually operating another switch. The B end is unlatched by operating a switch and the end effector is reattached as before. The latching and connection quality must be verified manually and the operation is slower but is potentially as safe as the automatic mode. The switches for the unlatch operation are interlocked so that only one end can be unlatched at a time, except for a special, guarded switch that jettisons the boom.

6.6.6.3 Actuator Gear Backlash

The dual drive train used in the boom actuators can be operated to eliminate gear backlash when the joint is stopped simply by allowing one drive unit to "back" the other as they stop. This feature can be incorporated in the computer programming for control of the boom.

SEQUENCE

Insert & Latch End 2 Into Root 2.

Limit Switch Confirms "Home" Position By Indicator.

Operator Switches Control 1→2.

Computer Checks Limit Switch, Connector, Video, Readdresses Actuators.

Computer Enables Unlatch Of End 1.

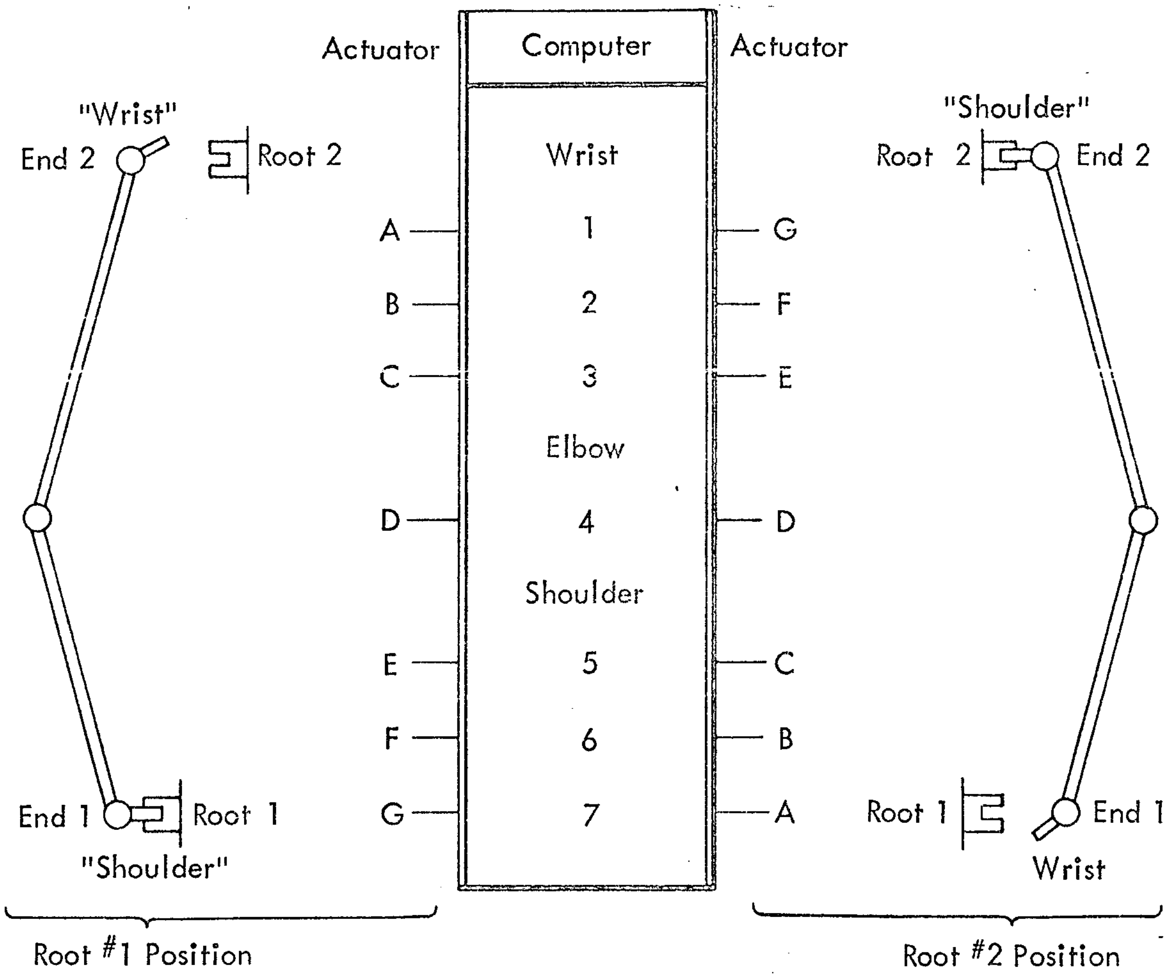


FIGURE 6.6-15
END POINT CONTROL TRANSFER

6.6.6.4 Electronic Damping

The boom and load are essentially alightly damped spring-mass system. Undamped the equation of motion where the boom is perturbed by f(t) is:

$$m\ddot{x} = -K_s x + f(t)$$

$$ms^2 X(s) + K_s X(s) = F(s)$$

$$\frac{X(s)}{F(s)} = \frac{\frac{1}{m}}{s^2 + \frac{K_s}{m}}$$

After the boom is perturbed by f(t), the output end will oscillate with a constant amplitude oscillation (actually, lightly damped).

$$\dot{x}(t) = K \sin \omega_n t, \text{where } \omega_n = \sqrt{\frac{K_s}{m}}$$

Since the actuator is not back-drivable, the load torques are not reflected at the motor. The nonback-drivability arises from friction in the gear train, imposing a limiting upper value on the numerical gear ratio. The condition is analogous to a screw jack that is designed to not back down under load,(Figure 6.6-16).The force W is the load and θ is the angle of lead of the screw. The force W sin θ is the force attempting to back the screw jack down. This force is opposed by the force of friction due to the coefficient of friction and the normal force ie:

$$F = \mu N = \mu W \cos\theta$$

If the coefficient of friction is large enough, F will be greater than W sin θ and the jack will not back down. That is, if $\varphi \geq \theta$ or $W \sin \theta = \mu N = W \mu \cos \theta$.

$$\mu = \frac{\sin \theta}{\cos \theta} = \tan \theta = \frac{h}{2\pi r}$$

W = Load
θ = Angle of lead screw
N = Normal force
r = Pitch radius of output gear
h = Lead screw pitch per turn
F = Friction force
μ = Coefficient of friction
n = Gear ratio = $\frac{2\pi r}{h}$

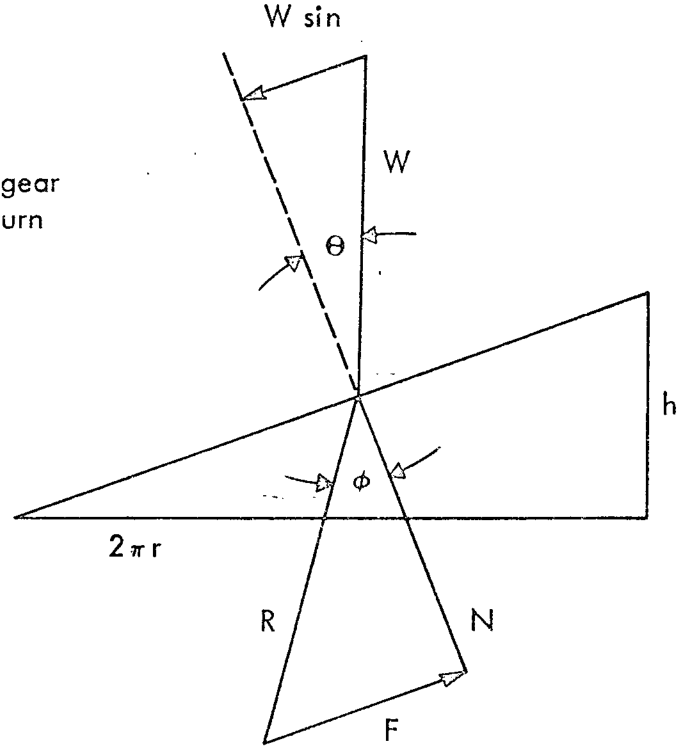
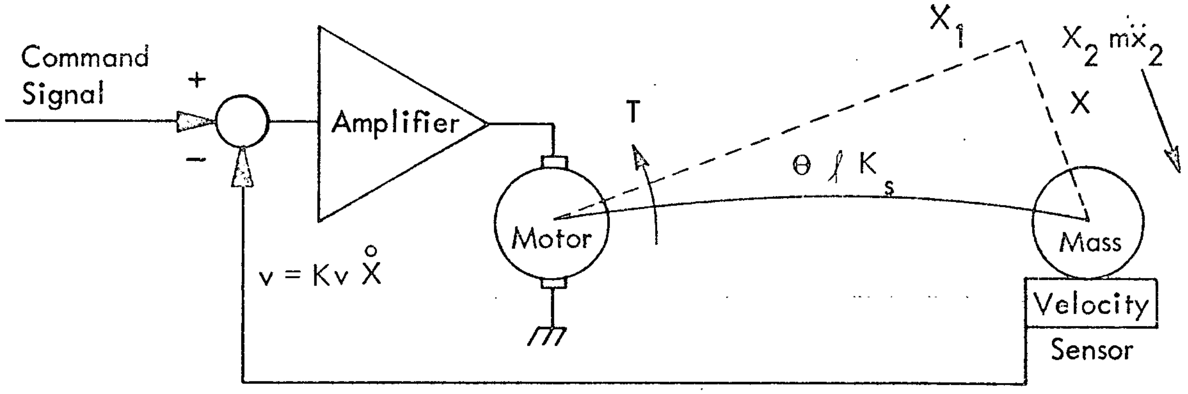


FIGURE 6.6-16
LEAD SCREW LOAD FORCE DIAGRAM



Damping Schematic

FIGURE 6.6-17
OSCILLATING BOOM FORCE DIAGRAM

Thus if the coefficient of friction is equal to or greater than the reciprocal of the gear ratio the lead screw is non-back-driveable for any load. Or in other words, a worm drive (lead screw) becomes non-back-driveable when its gear ratio is equal to or greater than the reciprocal of the coefficient of friction between the gears. An analogus situation exists for spur gears such as used in the selected actuators. Insofar as the actuators are concerned, the frictional effect is nonlinear and does not lend to analytical analysis. Nonlinear analysis can be done on an analog computer or by digital computer analysis. An approximate analysis can be made using the motor as a transducer actuated drive.

What is required to damp the system is a force that is a function of the boom tip dynamic motion. The acceleration can be sensed at the tip of the boom and summed with the actuation signal at the amplifier and fed back to the motor to induce damping. The force diagram for this case is shown in Figure 6.6-17. Using the symbols given in Table 6.6-2, the equations of motion can be written as follows:

TABLE 6.6-2
SYMBOLS USED FOR DYNAMIC DAMPING ANALYSIS

m = the mass of the load

X, x = the displacement variable

K_s = the spring constant

ℓ = the length of the boom

S = the Laplace variable

K_n = the motor speed constant

θ = the angular displacement variable

K_t = the motor torque constant

R = the motor armature resistance

A = the amplifier gain

K_a = the coefficient of the acceleration transducer

I = the motor armature current

T = torque

ζ = the damping

ω_n = the natural resonant frequency

$U_{-1}(t)$ = the unit step function, $U_{-1}(t) = 0$, $t < 0$, $U_{-1}(t) = 1$, $t > 0$

$$m\ddot{x}_2 = K_s\,(x_1 - x_2)$$

$$T_m = K_s \ell (x_1 - x_2)$$

$$m\ddot{x}_2 = \frac{T_m}{\ell}$$

$$T_m = K_t I$$

$$V_m = K_n \dot{\theta} + IR$$

$$T_m = \frac{K_t V_m}{R} - \frac{K_t K_n \dot{\theta}}{R}$$

And also $V_m = A\,(V_{in} - K_a \ddot{x}_2)$

Then $m\ddot{x}_2 = \dfrac{K_t V_m}{R\ell} - \dfrac{K_t K_n \dot{\theta}}{R\ell}$

$$m\ddot{x}_2 = \frac{K_t A}{R\ell} V_{in} - \frac{K_t A K_a \ddot{x}_2}{R\ell} - \frac{K_t K_n \dot{\theta}}{R\ell}$$

But $\ell \theta = x_1$

$$x_1 = \frac{m\ddot{x}_2}{K_s} + x_2$$

Then $m\ddot{x}_2 = \dfrac{K_t A}{R\ell} V_{in} - \dfrac{K_t A K_a}{R\ell} \ddot{x}_2 - \dfrac{K_t K_n m}{R\ell^2 K_s} \dddot{x}_2 - \dfrac{K_t K_n}{R\ell^2} \dot{x}_2$

$$\frac{K_t K_n m}{R\ell^2 K_s} \dddot{x}_2 + m\ddot{x}_2 + \frac{K_t A K_a}{R\ell} \ddot{x}_2 + \frac{K_t K_n}{R\ell^2} \dot{x}_2 = \frac{K_t A}{R\ell} V_{in}$$

$$\frac{K_t K_n m}{R\ell^2 K_s} S^3 X_2{}^{(s)} + mS^2 X_2{}^{(s)} + \frac{K_t A K_a}{R\ell} S^2 X_2{}^{(s)} + \frac{K_t K_n}{R\ell^2} S X_2{}^{(s)}$$

$$= \frac{K_t A}{R\ell} V_{in}{}^{(s)}$$

$$\frac{X_2(s)}{V_{in}(s)} = \frac{\dfrac{K_tA}{R\ell}}{\dfrac{K_tK_nm}{R\ell^2K_s}S^3 + mS^2 + \dfrac{K_tAK_a}{R\ell}S^2 + \dfrac{K_tK_n}{R\ell^2}S}$$

$$\frac{X_2(s)}{V_{in}(s)} = \frac{\dfrac{\ell K_sK_tA}{K_nm}}{S\left(S^2 + \dfrac{R\ell^2K_s}{K_tK_n}S + \dfrac{AK_a\ell K_s}{K_nm}S + \dfrac{K_s}{m}\right)}$$

This is a stable response for most inputs and has a damping factor that is a function of the fixed constants but is also a function of variables K_a, the sensitivity of the accelerometer and A, the gain of the amplifier.

The resonant frequency is $f_n = \dfrac{\omega_n}{2\pi} = \dfrac{1}{2\pi}\sqrt{\dfrac{K_s}{m}}$

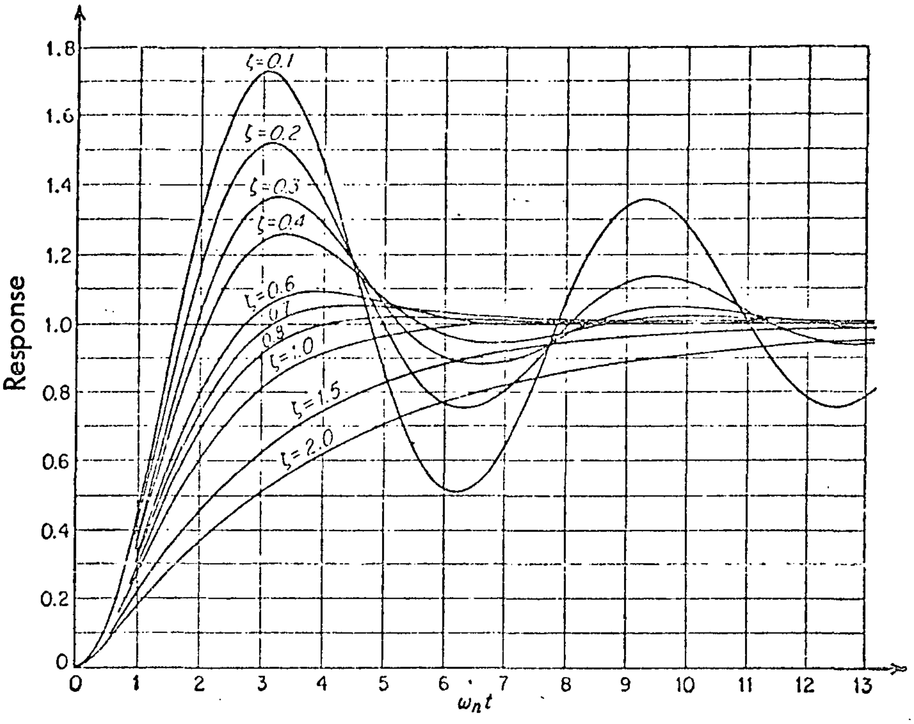
The damping factor ζ is $\zeta = \dfrac{R\,\ell^2\sqrt{K_sm}}{K_tK_n} + \dfrac{AK_a\,\ell\sqrt{K_s}}{K_n\sqrt{m}}$

The general form of the response to a unit step input $V_{in}(t) = U_{-1}(t)$ is

$$\dot{x}(t) = K'U_{-1}(t) - K''\varepsilon^{-\zeta\omega_nt}\sin(\omega_nt + \phi)$$

Typical response curves as shown in Figure 6.6-18.

The gain can be set to result in fast settling time and no overshoot. The damping must be done for all three degrees of translational freedom and for both joints, shoulder and elbow that effect the damping of the tip motion. The rotational deflection will not affect the sensed motions due to the high torsional stiffness and small angular deflection of the boom. In principle, electronic induced damping could be used in rotation, if necessary. The acceleration vectors will have to be resolved into components and fed to the amplifiers of the actuators controlling the appropriate motions. The digital computer is well suited to this task.



Response For Unit Step Input

FIGURE 6.6-18
ELECTRONIC CONTROLLED DAMPING

6.7 Data Processing and Transmission Analysis and Design

The data processing and transmission (telecommunication) system consists of two subsystems, each determined by the type of data to be transmitted: (1) the command and monitor subsystem where the signals are characterized by relatively low bandwidth (1 - 1000 Hertz) and fairly high accuracy requirements (in some cases on the order of 0.1%); and (2) the video subsystem where the signals have wide bandwidth (≥4 MHz) and medium (1%) accuracy/resolution requirements. A brief review is given below of the design factors leading to selection of parallel pulse code modulated (PCM) and hand-wired parallel coax RF systems for the above type (1) and (2) subsystems respectively. A description of their system parameters is also given. It should be noted that the selected telecommunication equipment is state-of-the-art and almost available on an "off-the-shelf" basis.

6.7.1 Design Factors Leading to Selected Systems

6.7.1.1 Design Impacts

The impact of overall manipulator system design decisions on the telecommunications subsystem include the following:

(1) Any direct (hard-line) communications to and from the boom through the attachment point must be double-ended, i.e., must be capable of being transmitted through either end (or both) of the boom.

(2) The direct (hard-line) transmission path from the boom to the control point will be altered during operation by having a different section of transmission line inserted or removed. The telecommunications system must be designed to operate during these transition times without error.

(3) The electrical connections at the end of the boom must be made and broken reliably many times, with long periods of inactivity in between use. The problems of contact welding in space, and reliability problems

of making and breaking multicontact connectors implies that the electrical connector design on each end of the boom will be critical. (This subject is treated in more detail in Section 6.3.5 "Boom/Root Point Electrical Connectors".)

(4) All command and monitor signals must interface with the computer.

(5) The electronics and telecommunication systems for the command and monitor systems must be capable of interfacing simultaneously with the shuttle and the space station.

6.7.1.2 System Considerations

(1) Reliability. The boom system must operate in all configurations continuously, without control signal failure for an extended period. This implies that control signals may have errors induced by the transmission system only if the errors can be detected and rejected, and if the durations of such errors are so short that the system response is not degraded. (1-2 milliseconds.)

(2) Physical Characteristics. The usual constraints of light weight, low power, and small size for space electronics are applicable here also, although not to the extreme extent implied in previous satellite electronics.

6.7.1.3 Design Decisions

(1) Hard Line vs. RF. The mobility requirements of the boom implies that free space transmission path from the boom to the station is variable. The problems of multi-path, signal strength, etc., for a varying transmission path in the presence of the complicated

"ground" structure of the station, (which may actually act as a re-radiator at some frequencies), coupled with the fact that the station configuration will change with time, pose a transmission path problem which is not realistically solvable by use of antennas. The requirements for essentially error free transmission of the command and monitor signals imply that the transmission path be known at all times. For these reasons a "hard-line"; i. e., known transmission path, was selected for all signals; command, monitor and TV.

(2) Analog vs. Digital Transmission. The controller for the system is a digital computer which implies that all control signals are in digital form at some time. Since it is easier to transmit digital, rather than analog, signals in the presence of noise, and easier to detect the presence of errors injected by the transmission process, digital transmission for control signals was selected.

The television camera and the human eye are analog systems. It is desirable to maintain the analog character of the TV signals if possible. Digitizing TV signals to be transmitted is warranted only if the noise of the transmission path is high, which is not the case here. The simplest transmission system, which is satisfactory for all the TV requirements is via compensated co-axial cable.

(3) External Transmission (Video). TV transmission of television signals to points external to the station or shuttle will be handled by their facilities and will not be considered further in this report.

6.7.1.4 Control Signal Transmission

The data transmission requirements are summarized in Table 6.7-1. Several general transmission system types were evaluated.

(1) Direct analog multi-wire between boom and control point, with A-D and D-A conversion being done at the control point. This system has the advantages that it has the minimum amount of electronics in the boom, but the multi-conductor cable requirements become excessive and noise rejection is poor.

(2) Serial PCM. The A-D conversion is done at the boom and the control point for the monitor and command signals respectively. This system requires the minimum number of wires from the control point to the boom. But the problems of transmission in an essentially unterminated system become difficult at high bit rates.

(3) Parallel PCM. Much the same system as paragraph (2) above, but the required bit rates on each wire are reduced. This permits operating with an improperly terminated transmission system.

6.7.1.5 Television Signal Transmission

Given the selection of a "known" or "hard-line" transmission system, (as opposed to a "R.F. link"), the major decision left to be made is whether to enclode the TV signals digitally for transmission. Since there is no advantage in this system to such encoding, it was rejected. The television transmission requirements are shown in Table 6.7-2.

6.7.2 Parametric Description

6.7.2.1 Control System

(1) Buss. The wiring internal to the station is multi-conductor cable (25 wire) #26 or smaller, terminated in approximately 200 ohm resistors.

Function	Number			Rate / Sec	Bits			Words / Sec
	Boom	Dextrous T/O	Viewing Boom		Address	Command	Monitor	
Monitor Arm Force	7	14	6	100	8	0	10	2700
Command Arm Force	7	14	6	100	8	10	0	2700
Monitor Arm Position	7	14	6	100	8	0	10	2700
Monitor T/O Housekeeping	30	60	20	1	8	0	10	110
Command TV Control	4	4*	2	10	8	10	0	110
Monitor TV Housekeeping	20	20	10	10	8	0	10	500

Notes:

*Commands Are Bang-Bang Rate On Off Control
2 PCM Command Words = 20 Bits = 10 Commands
On/Off Focus Zoom Light Iris Adjust B/W
Adjust Color (5) Adjust Stereo/Foveal (5)

TABLE 6.7-1
CONTROL SIGNAL DATA TRANSMISSION REQUIREMENTS

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

TABLE 6.7-2
TV SIGNALS GENERATED ON THE MAIN BOOM AND DEXTEROUS END EFFECTOR

(2) Connectors. The connectors between the core modules and the station modules are multiple circular connectors which can be made by hand after the mechanical mating of the module and central axis elements have been performed. There are no connectors as such on the shuttle, i. e., all wiring will be in place.

(3) Buss Driver. The buss drivers for the control command system are located at the computer. The buss lines are held high by the terminating resistors and asserted low by the drivers. Drivers for the monitor signals are located in the boom.

6.7.2.2 Television System

(1) Cable. The cable used to transmit the TV signal is miniature coaxial cable 0.25 cm (0.1") diameter or less, weighing less than 15 gms/m (10^{-2} lbs/ft).

(2) Connectors. Miniature coaxial connectors made by hand after the central axis elements and station modules are mechanically connected. No such connector requirements exist on the shuttle.

(3) Switching. Each central axis element will have a single pole multiple throw switch to connect the correct network set of coaxial cables between the cameras and the monitors (see Figure 6.7-1).

6.7.3 Interfaces

(1) Control Telecommunications to computer. This is a standard interface of the "Omnibus" (PDP-8E) type.

(2) Wiring. The station central axis elements and station modules will have to be wired for the control buss and TV cable/switch system. Comparable wiring will be required for the shuttle.

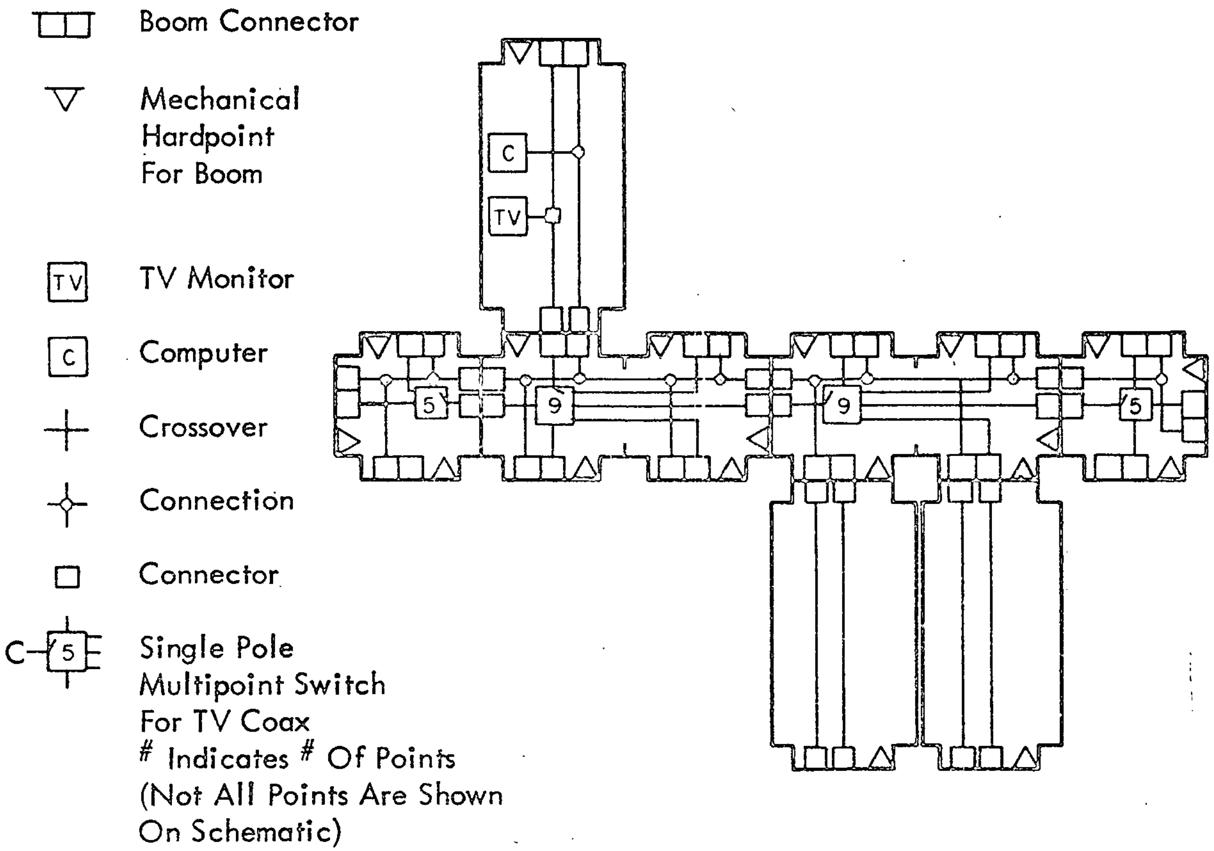


FIGURE 6.7-1
SPACE STATION DISTRIBUTION SCHEMATIC DIAGRAM

(3) Time Sharing. Sharing of the control buss and TV signal cables with the station/shuttle experiment control computer and/or sharing the station shuttle computer should be investigated as soon as the respective systems become more definite.

6.7.4 Sensitivity

The telecommunications system has been conceived to be relatively insensitive to changes in input parameters, such as accuracy, distance, etc. The weight of the telecommunications system increases linearly with the sum of the lengths of the central axes of the modules and the central axis element. The power taken by the telecommunications system is only a slight function of the size of the system. The number of wires in the address portion of the control buss is increased by one for a doubling of the number of commands and monitors.

The number of wires in the data portion of the control buss is increased by one for a doubling of the accuracy requirements. The number of coaxial cables in each station module is equal to the number of TV cameras on the boom. The number of coaxial cables in the central axis element is equal to the total number of cameras.

6.8 System Weight and Size Analysis

The design drivers which determine the manipulator system weight and trade off 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	As required to accomplish tasks	Study general requirements
	Reach		
	Mobility		
3	Tip Force Level	As required to accomplish tasks	Study general requirements
	Deflection		

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. (See sections 2.0 "Summary", 3.1 "Boom Design and Analysis", 3.3 "Visual System", 3.5 "Utility", "6.3 Boom Mechanical Analysis and Design" and 6.5 "Visual System Analysis and Design"). 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 the report (as noted below) for further detail on the trade offs.

6.8.1 System Weight Summary

6.8.1.1 The Overall System

The overall system weight is summarized in Table 6.8-1. 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.

6.8.1.2 Control Console

The control console weight summary is given in Table 6.8-2. The weight alloted in Table 6.8-1 is slightly larger to allow for contingencys.

6.8.1.3 Auxiliary Viewing Boom

The auxiliary viewing boom weight summary is given in Table 6.8-3. Note that it includes the TV and illumination light assembly.

6.8.1.4 Root Points

The study ground rules (see Section 6.1 "Introduction") do not change 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 that about 10 m(~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 ≈ 3 Kg (6.6 lbs) each.

6.8.2 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 Section 3.13 "Weight and Deflection Trade Offs". Results of the material trade off studies are

TABLE 6.8-1

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 6.8-2

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 6.8-3

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 6.8-4. 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 6.8-5 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 6.8-1 and -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 6.8-1 and 6.8-2, the assumed deflection limit (taken about equal to the shuttle berthing center line misalignment - see Appendix A) 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 Section 6.3.2 "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

					Same (t, r, ℓ, σ_B)		Same (ζ, r, ℓ)			
Material	E (lb/in^2)	ρ (lb/in^3)	σ_{Tu} (lb/in^2)	σ_{Ty} (lb/in^2)	(ζ/ζ_{Al})	$\left(\frac{wt}{wt_{Al}}\right)$	$\left(\frac{t}{t_{Al}}\right)$	$\left(\frac{\sigma}{\sigma_{Al}}\right)$	$\left(\frac{wt}{wt_{Al}}\right)$	$\frac{F_{tip}}{F_{tip}Al}$
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	$*70 \times 10^3$	$*50 \times 10^3$	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 6.8-4
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 6.8-5
SUMMARY OF MANIPULATOR SYSTEM WEIGHT VS TIP FORCE

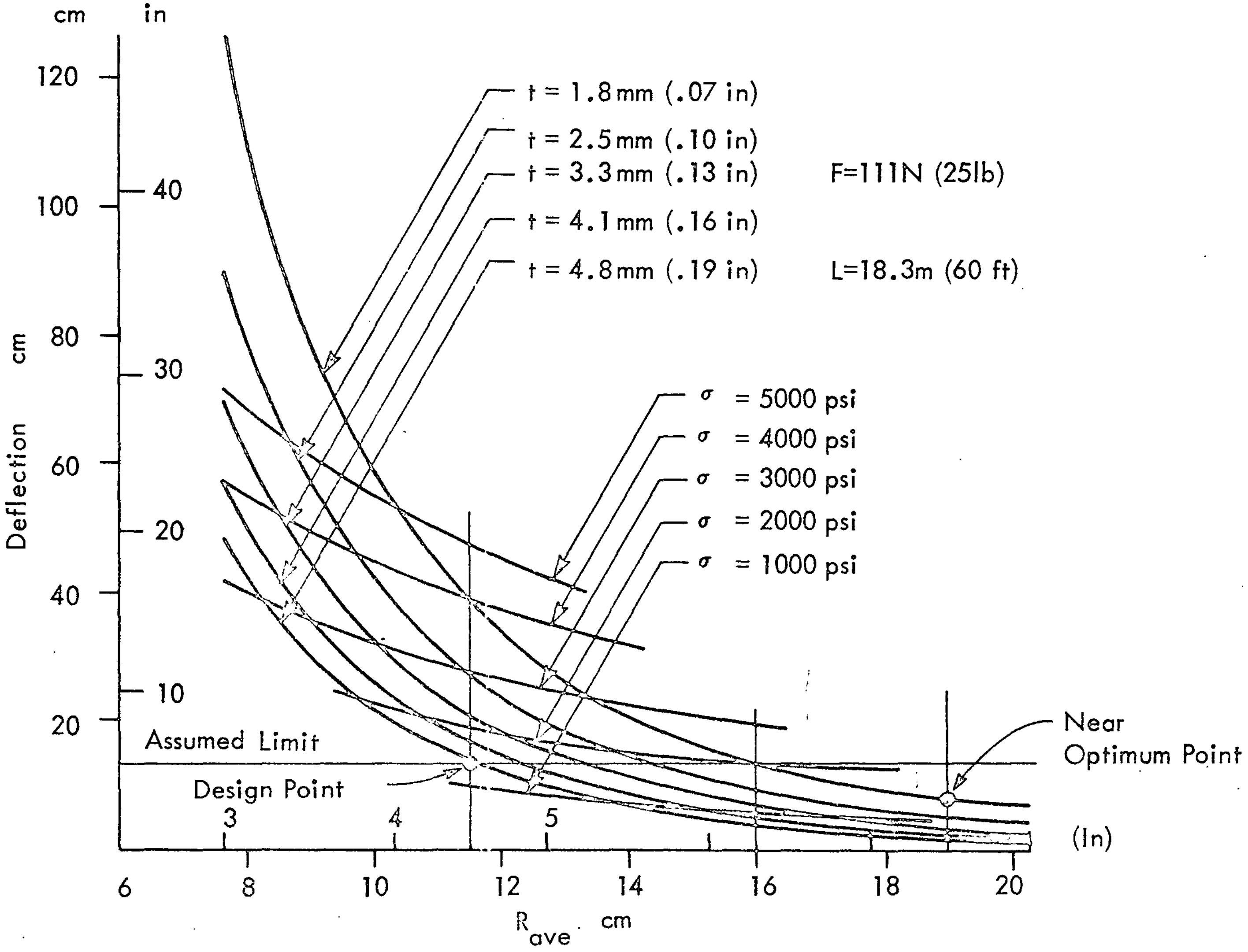


FIGURE 6.8-1
DEFLECTION TRADE OFF CURVES FOR ALUMINUM BOOM

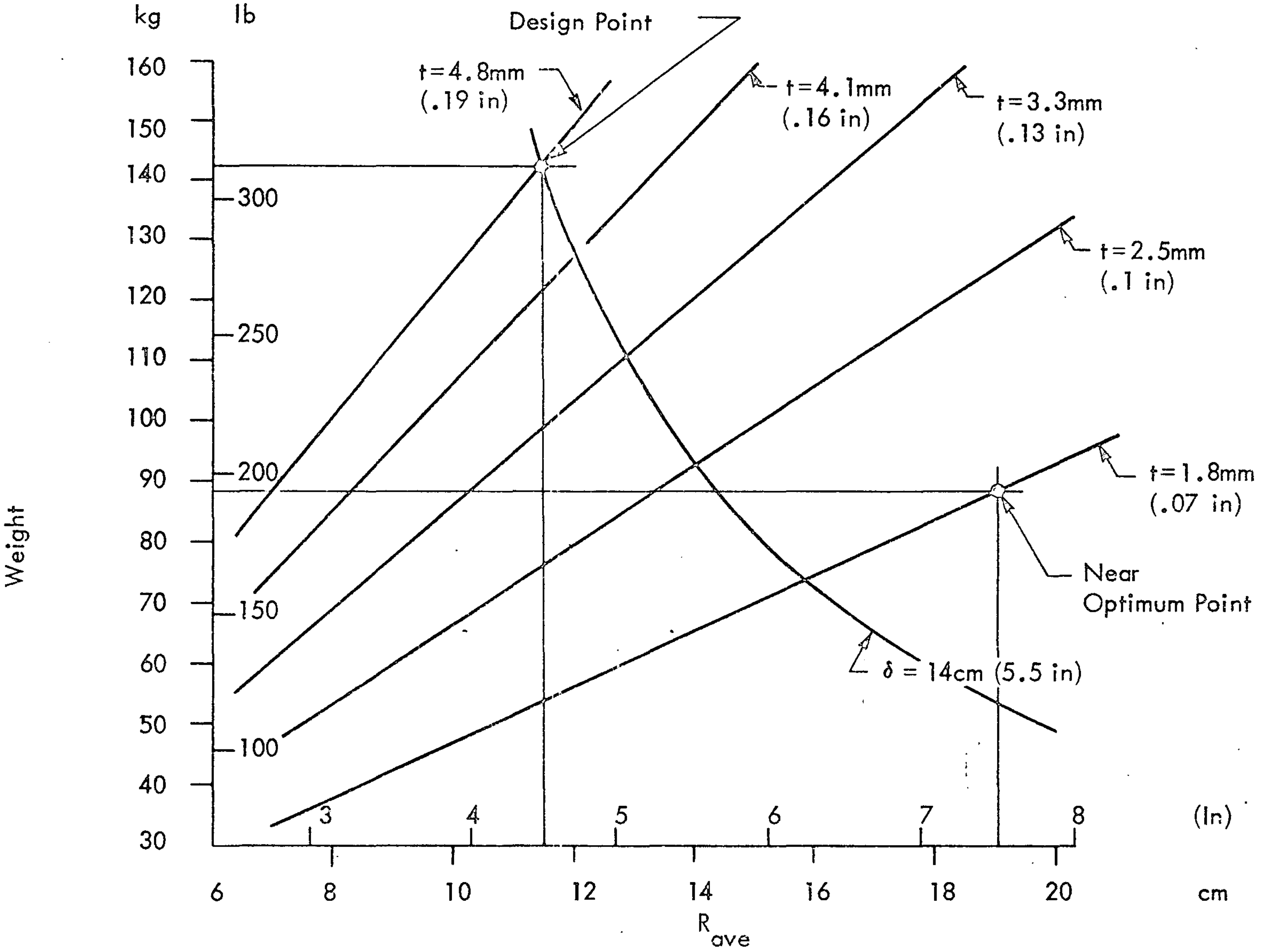


FIGURE 6.8-2
WEIGHT TRADE OFF CURVES FOR ALUMINUM BOOM

6.9 System Requirements Analysis

The manipulator system requirements based on the study initial requirements and results of the preliminary design effort are presented in Section 6.2 "Requirements". In general these requirements are not expressed quantitatively since further detailed design and simulation studies are required to do so. A brief summary of how the selected manipulator system meets the above requirements and study ground rules (see Section 6.1 "Introduction") is given below.

6.9.1 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.

6.9.2 Subsystem Requirements

6.9.2.1 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.

6.9.2.2 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.

6.9.2.3 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.

6.9.2.4 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.

6.9.2.5 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.

6.9.2.6 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.

6.9.3 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.

6.9.4 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.

6.10 System Utility Analysis

The cruciform type space station and the 040A shuttle were used as reference configurations to develop manipulator design parameters and study the general utility of the resulting system (see Appendix A). Considerations of manipulator applications/techniques for the first ten (10) shuttle missions (including the Large Space Telescope) and for space station assembly, maintenance and cargo handling are presented in Section 3.5 "Utility". Additional considerations not included in Section 3.5 are presented below.

6.10.1 Shuttle Direct Viewing and Root Point Arrays

The current viewing capability from the 040A shuttle and an approach for manipulator deployment are presented in Figures 6.4-1 and 3.5-1, respectively. As shown in Figure 3.5-1, the operator has no side, overhead or forward viewing capability. Greater viewing capability and manipulator deployment flexibility can be achieved by the approach illustrated in Figures 6.10-1 and -2 below. By reconfiguring the roof of the shuttle crew compartment to the "Astrodome" configuration the manipulator operator can achieve nearly a $2 \tilde{\pi}$ steradian solid angle viewing capability including the current 20° down view into the cargo bay. (As in the current shuttle concept, the cargo door fairings would cover the crew compartment roof in an aerodynamically streamlined fashion when closed.) By looking down a few degrees below the -20° view, the operator could see the manipulator control console in much the same way that a pilot observes the instrument panel on an aircraft. Preliminary experiments indicate that no objectionable "blind spots" occur between looking out and looking down at the control console. An adjustable platform would be required to accommodate a large range in operator size, but the current approach is faced with a similar problem; i.e., the operator must be elevated enough to see over the console.

An array of possible root point locations is illustrated in Figure 6.10-2. With the walking boom concept, fixed launch/transport storage rootpoints may be used. When the shuttle is in orbit, the manipulator can transfer to the

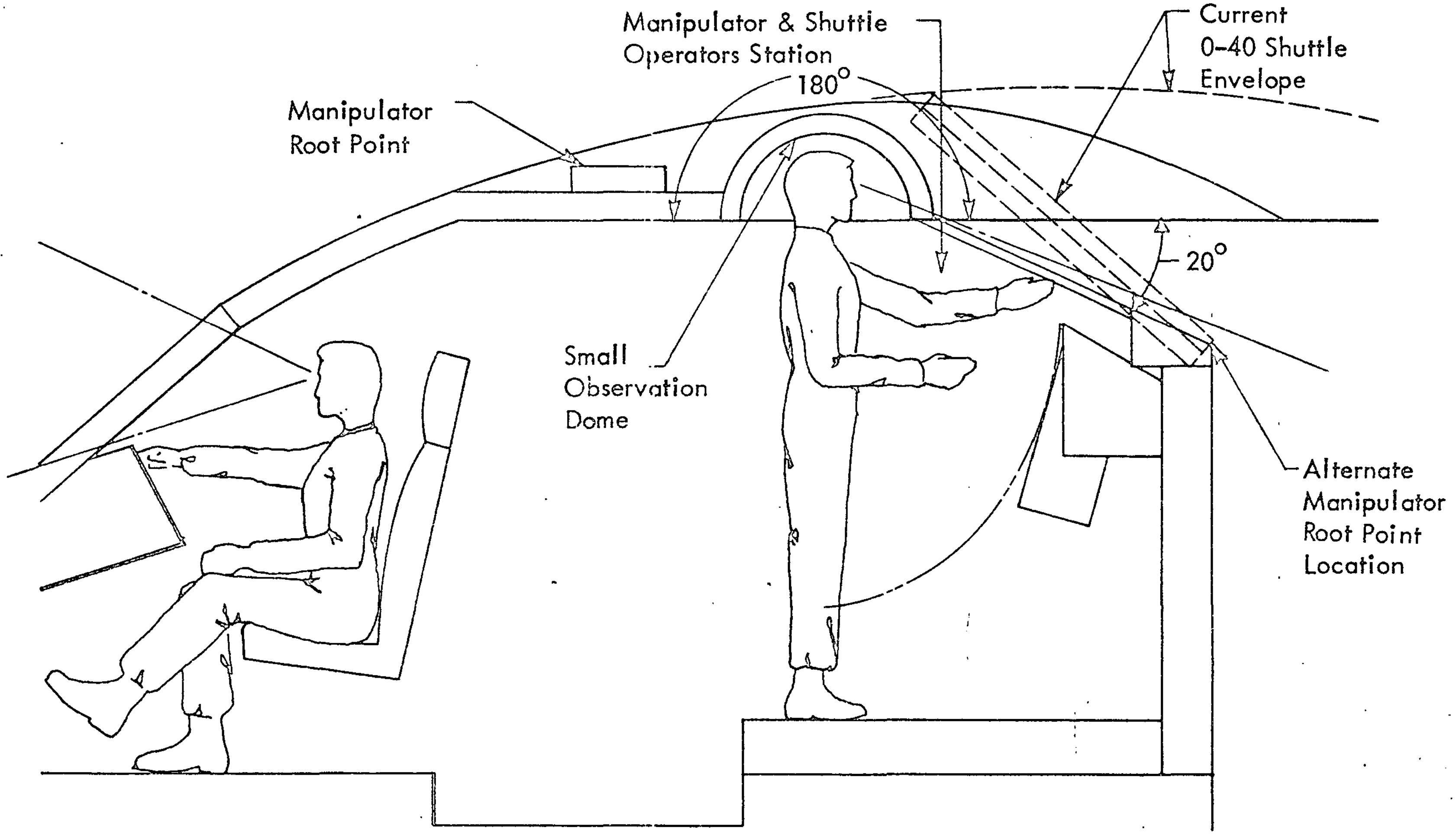


FIGURE 6.10-1
ASTRODOME VIEWING ARRANGEMENT

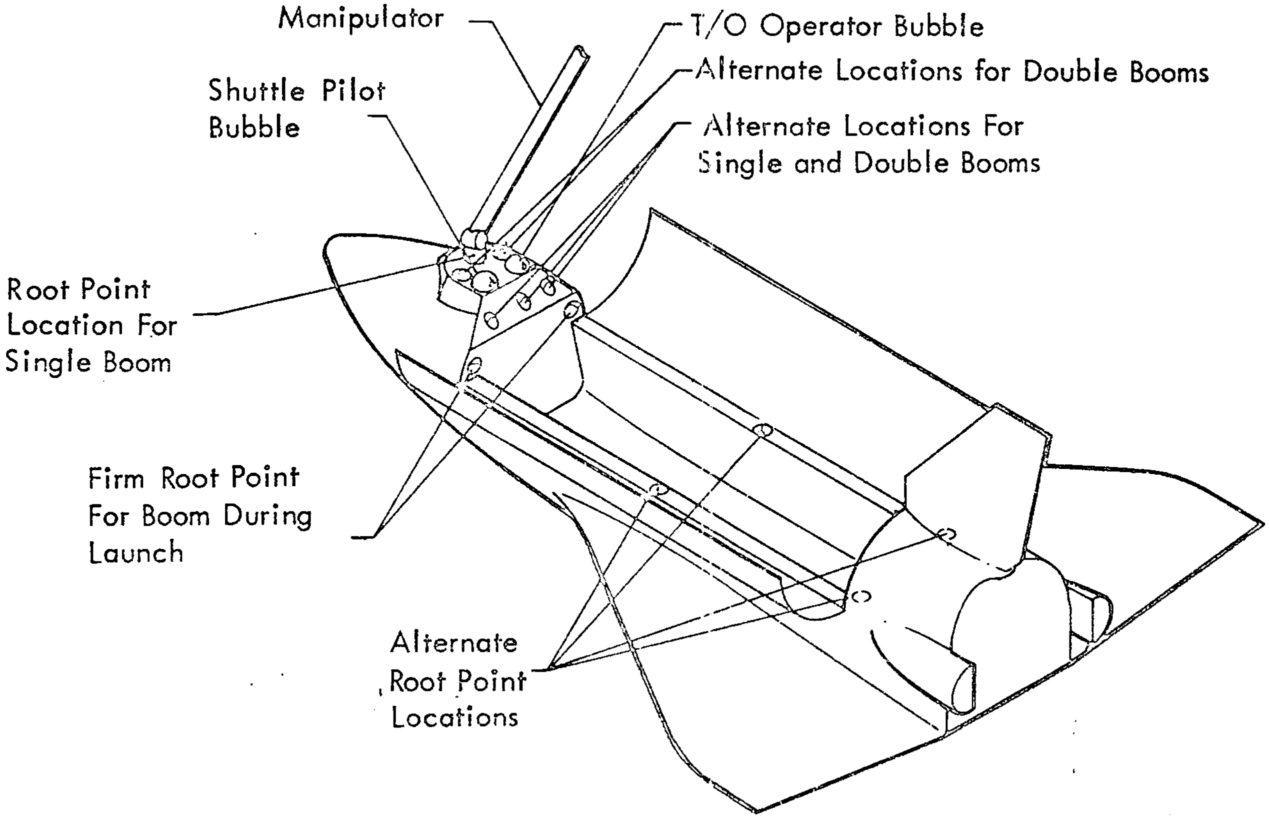


FIGURE 6.10-2
SHUTTLE ROOT POINT AND ASTRODOME CONCEPTS

desired (optimum for the task at hand) root point. Furthermore, either single or multiple booms may be used as required by the mission tasks. A single boom is shown attached to a root point above and forward of the operator. This location offers a minimum of viewing obstruction to the operator since he does not have to look around the boom as when it is attached directly in front of him. Note that double booms could be attached in a similar way.

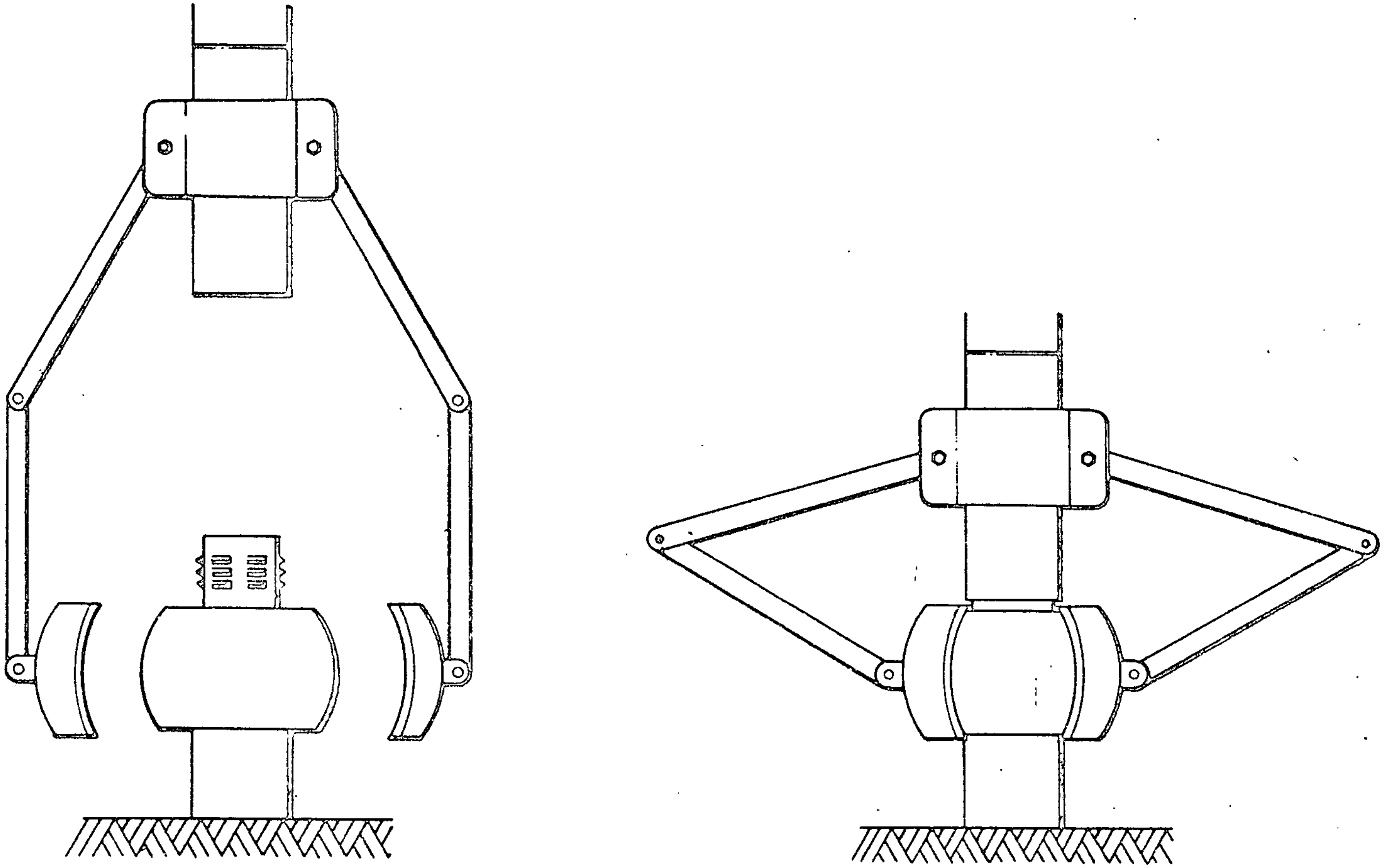
6.10.2 Shuttle Capture

The ground rule (see Section 6.1 "Introduction") 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 0.03 m/sec (0.1fps) 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 6.10-3. 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 6.10-3
SCHEMATIC SHUTTLE CAPTURE QUICK GRASP END EFFECTOR

6.10.3 Component/Tool Tote Box

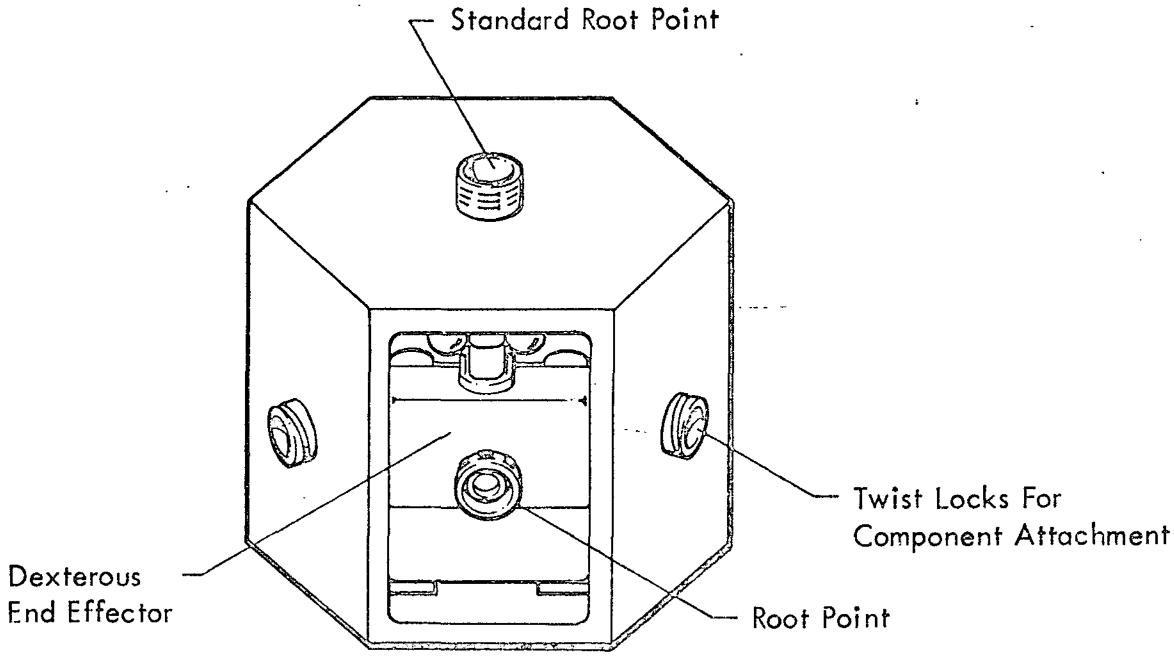
The requirements and selected techniques for manipulator boom mobility are discussed in Section 3.5 "Utility". If the boom is to do other than transfer/berthing operations, (such as replacing/repairing components on the station or perhaps even a satellite) a means for carrying and assessing such components and necessary tools is required. This can be accomplished with a tote box such as illustrated in Figure 6.10-4. The tote box itself is illustrated in Figure 6.10-4(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 6.10-4(b) to accomplish the task.

6.10.4 Dexterous End Effector

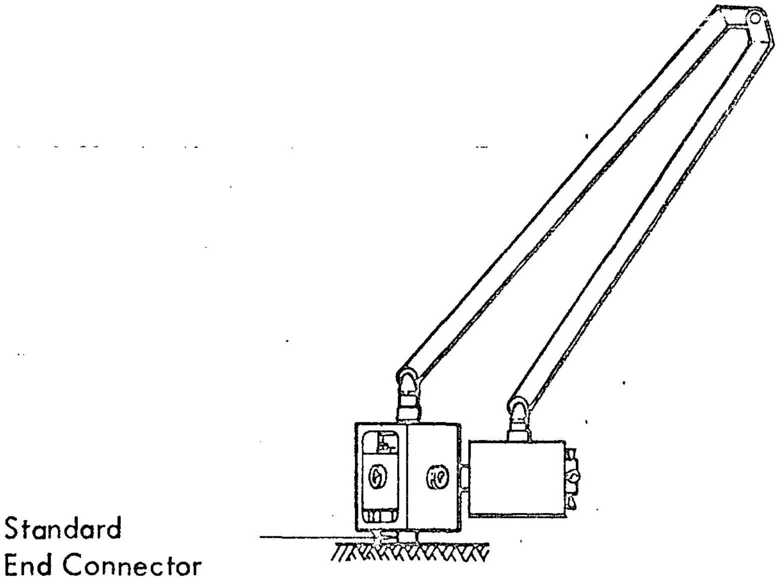
No attempt has been made to design a dexterous teleoperator end effector (TOEF) in this study; however, a schematic unit is illustrated in Figure 6.10-5. It incorporates the dual field, stereo-foveal/3 lamp camera and illumination assembly described in Section 6.5 "Visual System". It is not likely that 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 6.10-4
SCHEMATIC OF TOTE BOX CONCEPT

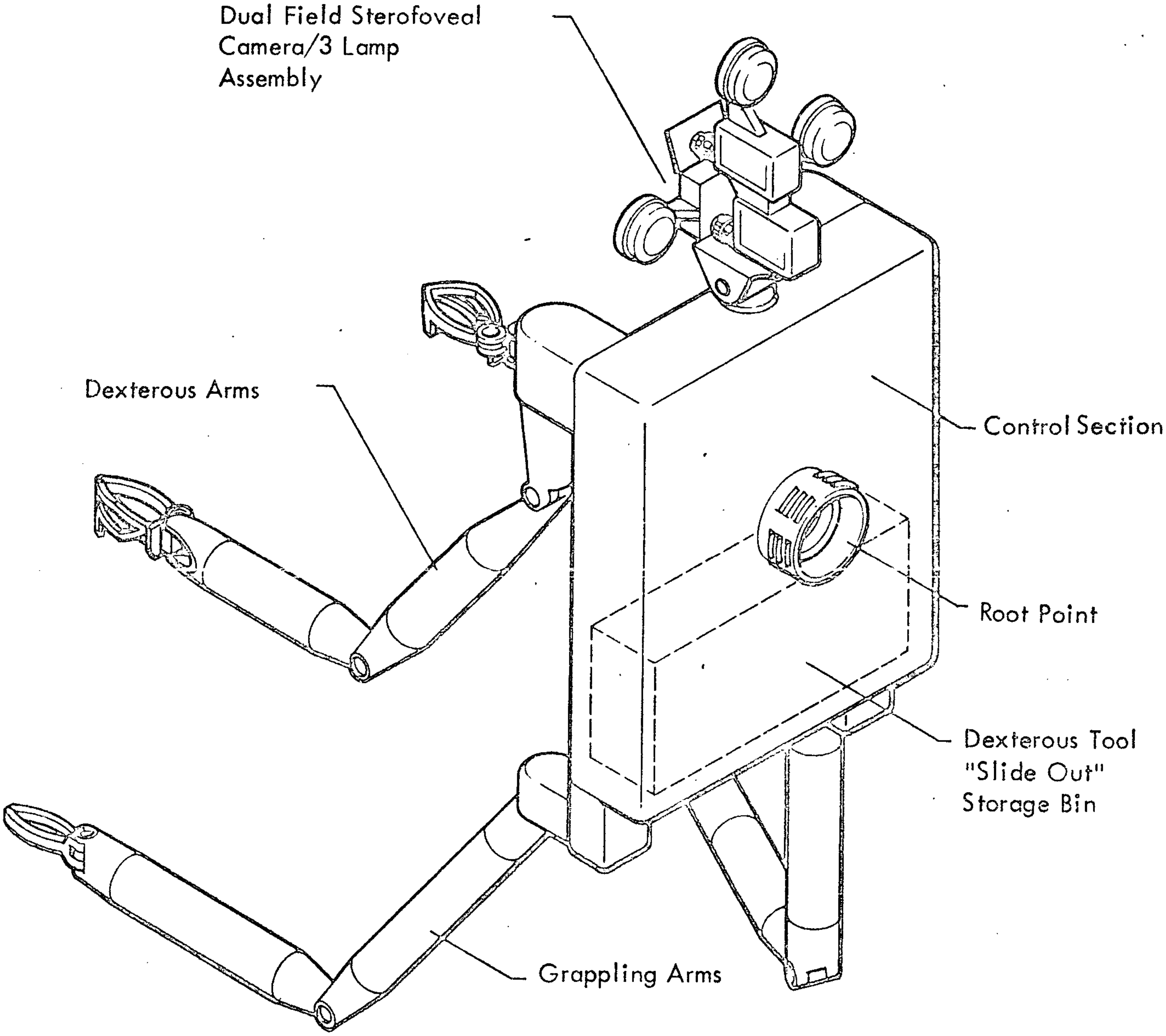


FIGURE 6.10-5
SCHEMATIC DEXTEROUS END EFFECTOR

illustrated in Figure 6.10-4(a).

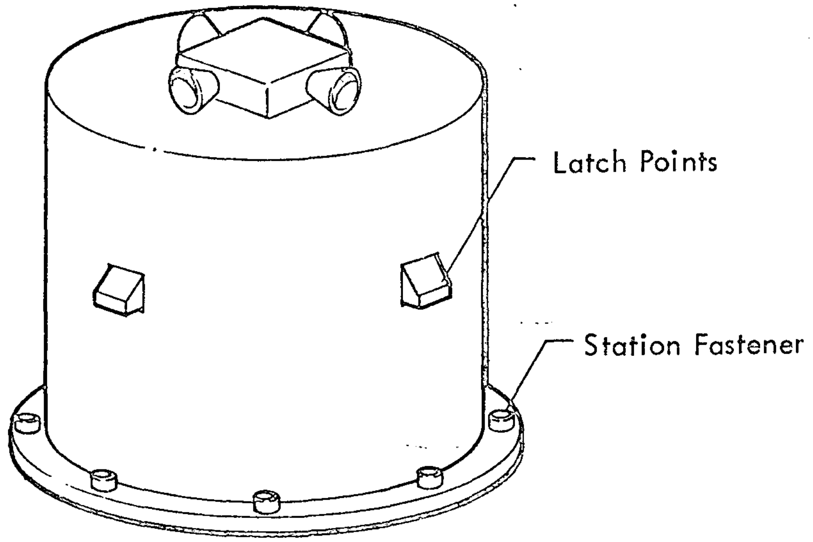
6.10-5 Propulsion Package Replacement

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.

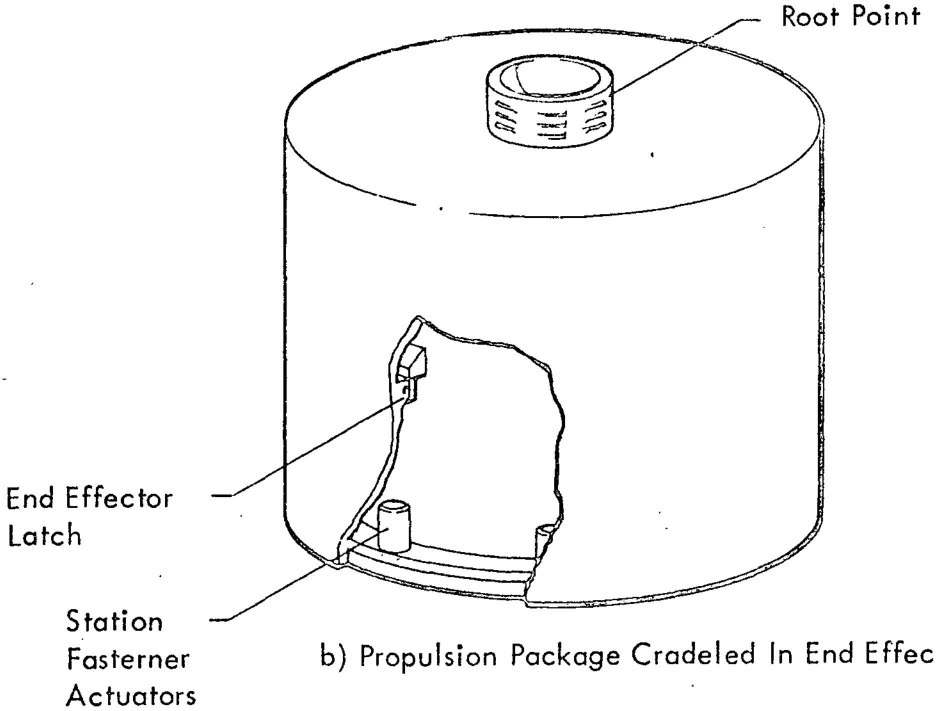
Such a special end effector is illustrated schematically in Figure 6.10-6. The propulsion package would incorporate passive alignment guides and catches such that the end effector could be slipped over the top, brought into proper alignment and latched to the unit. Individual actuators on the end effector 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 in Section 3.5 "Utility".

6.10-6 Manipulator/Space Systems Design Philosophy

From the discussion presented in Section 3.5 "Utility", this section and elsewhere in this report, 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 benifits 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. 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 6.10-6
SCHEMATIC PROPULSION PACKAGE END EFFECTOR

6.11 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. Technology requirements for the manipulator system are summarized in Section 2.5 "Technology Requirements". Specific problem areas identified as a result of this study are summarized below.

6.11.1 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.

6.11.2 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) 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.

6.11.3 Visual System

The viewing system has been designed to make maximum use of available equipment and techniques. However, development will be needed to 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.

6.11.4 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.

6.11.5 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.

6.11.6 End Effectors

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

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

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

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VII - INFORMATION PROVIDED BY HAMILTON STANDARD REGARDING ENVIRONMENTAL CONTROL SYSTEMS (ECS) AND LIFE SUPPORT SYSTEMS (LSS)

EC/LSS - 1. Lunar Module Environmental Control Subsystem
Explains the basic function and operation of the LM Environmental Control Subsystem (ECS) and lists the salient parameters of the subsystem components.

EC/LSS - 2. Apollo Portable Life Support System
Explains the basic function and operation and lists the salient components parameters for the following Second Generation Apollo Portable Life Support Elements

- a) Portable Life Support System (PLSS)
- b) Oxygen Purge System (OPS)
- c) Buddy Secondary Life Support System (BSLSS)
- d) Pressure Control Valve (PCV)

EC/LSS - 3. Space Shuttle Environmental Control/Life Support System
Oral briefing by H. S. on July 8, 1971 under contract No. NAS 1-10359.

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EC/LSS - 5. Space Station Prototype Environmental Thermal Control and Life Support System
August 1971 System Summary

EC/LSS - 6. Space Shuttle Orbitor Baseline EC/LSS
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EC/LSS - 7. Space Shuttle Environmental Control and Life Support System
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Section Chief
McDonnell Douglas Astronautics Company - West

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W. J. Ayotte
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APPENDICES

A) STATEMENT OF WORK

B) SHUTTLE AND SPACE STATION PARAMETERS

APPENDIX A

STATEMENT OF WORK

Exhibit A

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ENGINEERING AND DEVELOPMENT DIRECTORATE

STATEMENT OF WORK

FOR

PRELIMINARY DESIGN OF A
SPACE STATION ASSEMBLY AND
CARGO HANDLING SYSTEM

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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CONTENTS

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1.0 PURPOSE

1.1 OBJECTIVE

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

1.2 END PRODUCT

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

1.3 BACKGROUND

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

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

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2.0 SCOPE

2.1 GENERAL

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

2.2 PROGRAM SCHEDULE

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

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3.0 TECHNICAL REQUIREMENTS

3.1 GENERAL

3.1.1 STUDY REQUIREMENTS

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

3.1.2 DESIGN REQUIREMENTS

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

3.1.3 DEVELOPMENT REQUIREMENTS

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

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3.2 SYSTEM REQUIREMENTS

3.2.1 GENERAL REQUIREMENTS

One of the more promising techniques for establishing a space station in earth orbit involves the assembly of modules delivered to orbit by the space shuttle. This technique would also be applicable to the orbital assembly of other advanced systems such as large earth or earth synchronous, lunar, or planetary payloads where modular assembly is required. Fundamental to the concept of modular space station assembly is a technique for transferring the modules from the shuttle to a docking position on the station core element. An analysis and evaluation will be made on a T/O for transferring and maneuvering modules between a space shuttle and a modular space station. The T/O device shall consist of a manipulator boom articulated at shoulder, elbow, and wrist-type joints to accomplish the assembly of a modular space station and unloading and loading shuttle cargo. The contractor shall define the criteria and overall requirements of the device. The device should be designed to permit docking a module to a space station or other orbital module with very low closure rates and with very precise control so that the docking loads are small enough to be absorbed by the device, thereby relieving the requirement for attenuating large docking loads. The baseline T/O will be space station attached and will consist of a manned module which can dock on any of the stations docking ports and which possesses one or more manipulator booms. The space station modules considered will be shuttle launched. The basic T/O functions will be the docking and assembly of the modules onto a station core, cargo docking or cargo transfer to the completed station. A module of this basic type was postulated in the Pre-Phase A Study of a Shuttle-Launched Space Station developed by MSC and now under study by NAR. Attachment 2 contains sketches of the concept.

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

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

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3.2.2 SUBSYSTEM REQUIREMENTS

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

3.3 CONCEPT EVALUATION

3.3.1 TECHNOLOGY

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

3.3.2 KINEMATICS

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

3.3.3 INITIAL ANALYSIS

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

3.3.4 TELECOMMUNICATIONS

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

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

a. Conceptual approach, description and basis therefor.

b. Block diagram(s).

c. Parametric description of each element including weight, power, geometry, location, functional performance.

d. Interface descriptions and requirements on other subsystems.

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3.3.5 PRELIMINARY DESIGN

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

3.4 CONCEPT ANALYSIS

3.4.1 DETAIL REQUIREMENTS

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

3.4.2 DETAIL ANALYSIS

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

a. The method of controlling the articulation of the booms shall be specified. Any control augmentation required, such as limit switches, shall be considered.

b. The contractor shall perform an analysis to determine the maximum loads to which the booms may be subjected. A preliminary evaluation of the structural integrity of the arms shall be conducted.

c. Further dynamic analyses will be performed to determine the power required to actuate the device. Preliminary evaluations of the response characteristics of the device shall be determined.

d. Study and design effort of the Telecommunications subsystem shall consider as a minimum the following:

    (1) Hardline versus R.F. transmission.

    (2) Total signal requirements such as number of signals, signal characteristics, signal requirements versus operational time line, signal accuracies and allowable error rates.

    (3) Signal formats.

    (4) Transmission range.

    (5) Tracking/ranging requirements.

(6) Local signals versus remote, local computation.

(7) Multiplexing techniques.

(8) Bandwidth compression.

(9) Near field effects, antenna pattern obscuration, signal overloading, electromagnetic compatibility.

(10) Television light levels, lighting geometry, automatic light level compensation and protection.

(11) Television picture quality aspects such as field of view, depth of field, resolution, contrast range, grey shades, signal/noise, motion rendition, geometry distortion, controlled functions such as lens settings.

(12) Television display and control aspects such as scan conversion, head/eye aimed television cameras, human factors considerations such as monitor size.

e. The types of end effectors shall be investigated to the extent that they affect the design of the booms.

3.4.3 REQUIREMENTS ANALYSIS

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

3.4.4 UTILITY

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

3.5 DESIGN PARAMETERS

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

a. Design sensitivity curves with respect to input data.

b. Estimates of weight and volume.

c. Estimates of response capability.

d. Upgrading possibilities.

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e. Future problems.

f. Estimates of development time and cost.

3.6 MOCKUP DRAWINGS

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

3.7 PRELIMINARY DESIGN DRAWINGS

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

3.8 MAN-MACHINE INTERFACE

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

3.9 PROPULSION PACKAGE REPLACEMENT

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

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4.0 PROGRAM MANAGEMENT REQUIREMENT

4.1 ORGANIZATION REQUIREMENTS

Not applicable.

4.2 CONFERENCE REQUIREMENTS

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

4.3 CONFIGURATION MANAGEMENT REQUIREMENTS

Not appicalbe

4.4 PROGRAM CONTROL REQUIREMENTS

Not applicable

4.5 CONTRACTOR DATA MANAGEMENT

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

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

4.6 DOCUMENTATION REQUIREMENTS

4.6.1 GENERAL

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

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

4.6.2 DATA REQUIREMENTS LIST

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

4.6.3 REPORTING UNITS

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

4.7 INTERFACE REQUIREMENTS

Not applicable

4.8 FURTHER DEVELOPMENT PROGRAM

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

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5.0 SUPPORT REQUIREMENTS

5.1 GOVERNMENT-FURNISHED PROPERTY

Not applicable.

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6.0 QUALITY ASSURANCE

Not applicable.

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7.0 RELIABILITY

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

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

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

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8.0 SYSTEM SAFETY

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

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

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

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9.0 APPLICABLE DOCUMENTS

Not applicable.

APPENDIX B

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

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

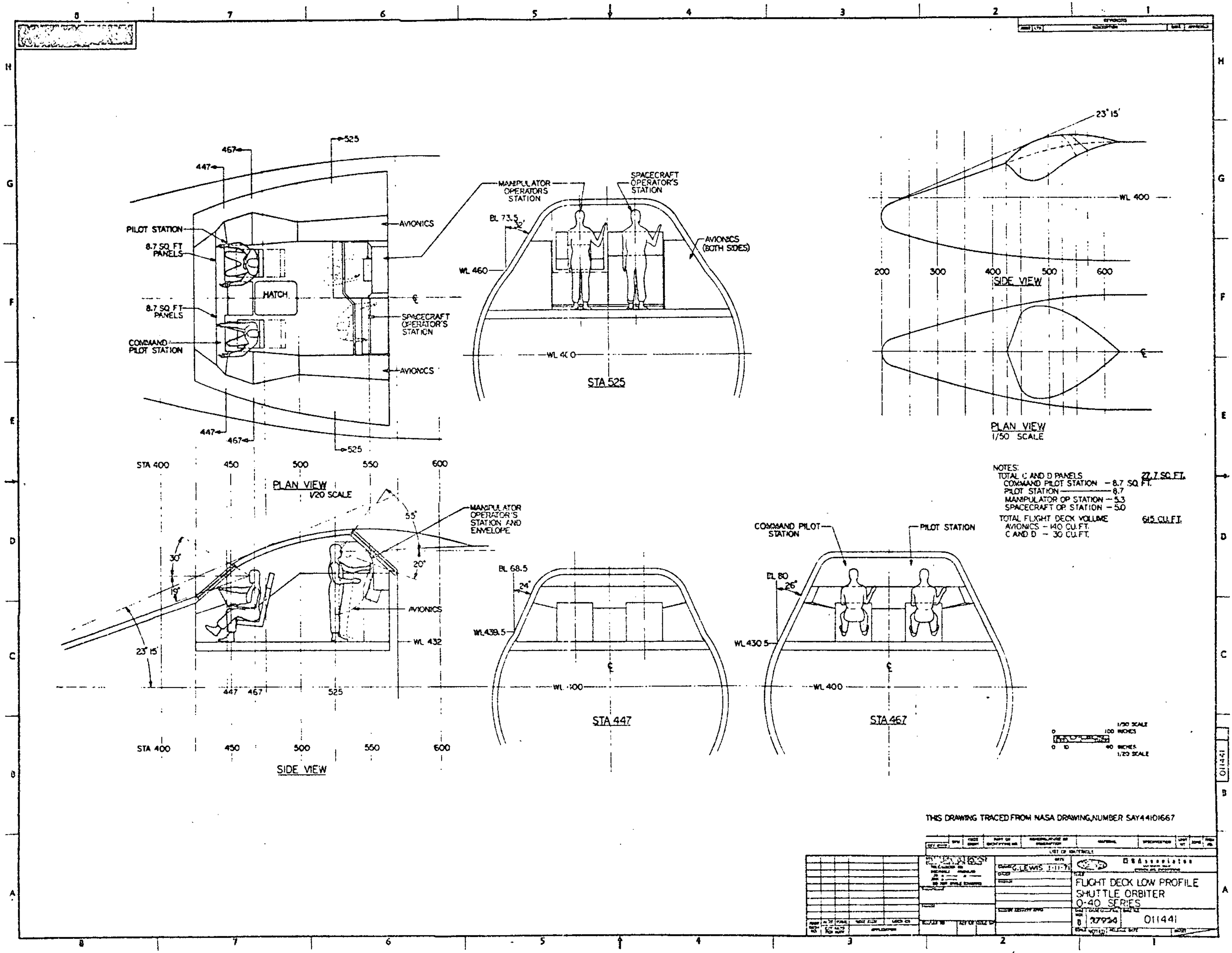
SHUTTLE DOCKING CLOSURE RATES AND MISALIGNMENTS

Centerline Miss Distance	± 0.1524 meters (6 inches)
Miss Angle	± 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)



NOTES:
TOTAL C AND D PANELS — 22.7 SQ. FT.
COMMAND PILOT STATION — 8.7 SQ. FT.
PILOT STATION — 8.7
MANIPULATOR OP STATION — 5.3
SPACECRAFT OP STATION — 5.0
TOTAL FLIGHT DECK VOLUME — 615 CU. FT.
AVIONICS — 140 CU. FT.
C AND D — 30 CU. FT.

THIS DRAWING TRACED FROM NASA DRAWING, NUMBER SAY44101667

FIGURE B-1
040A SHUTTLE CREW COMPARTMENT

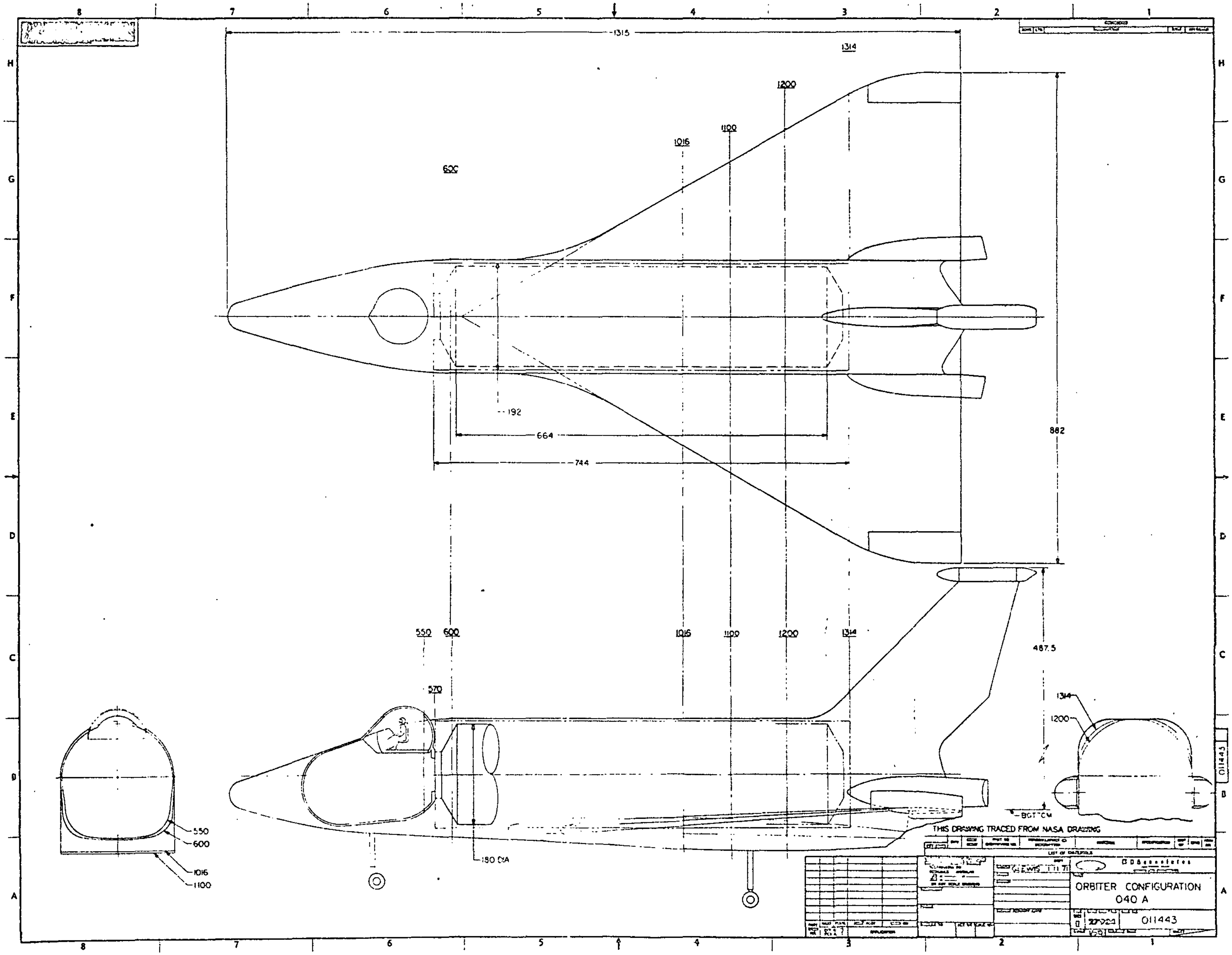
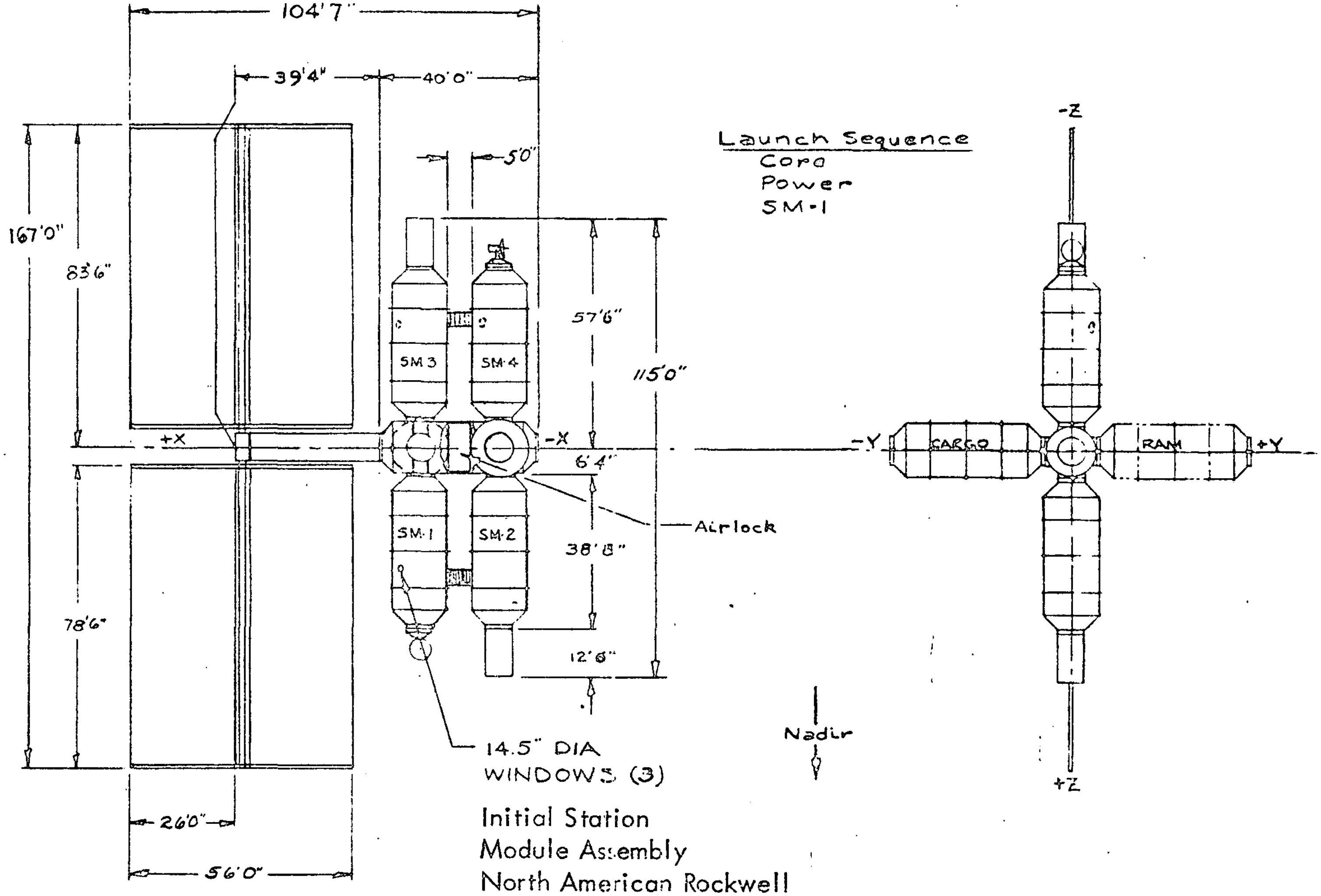
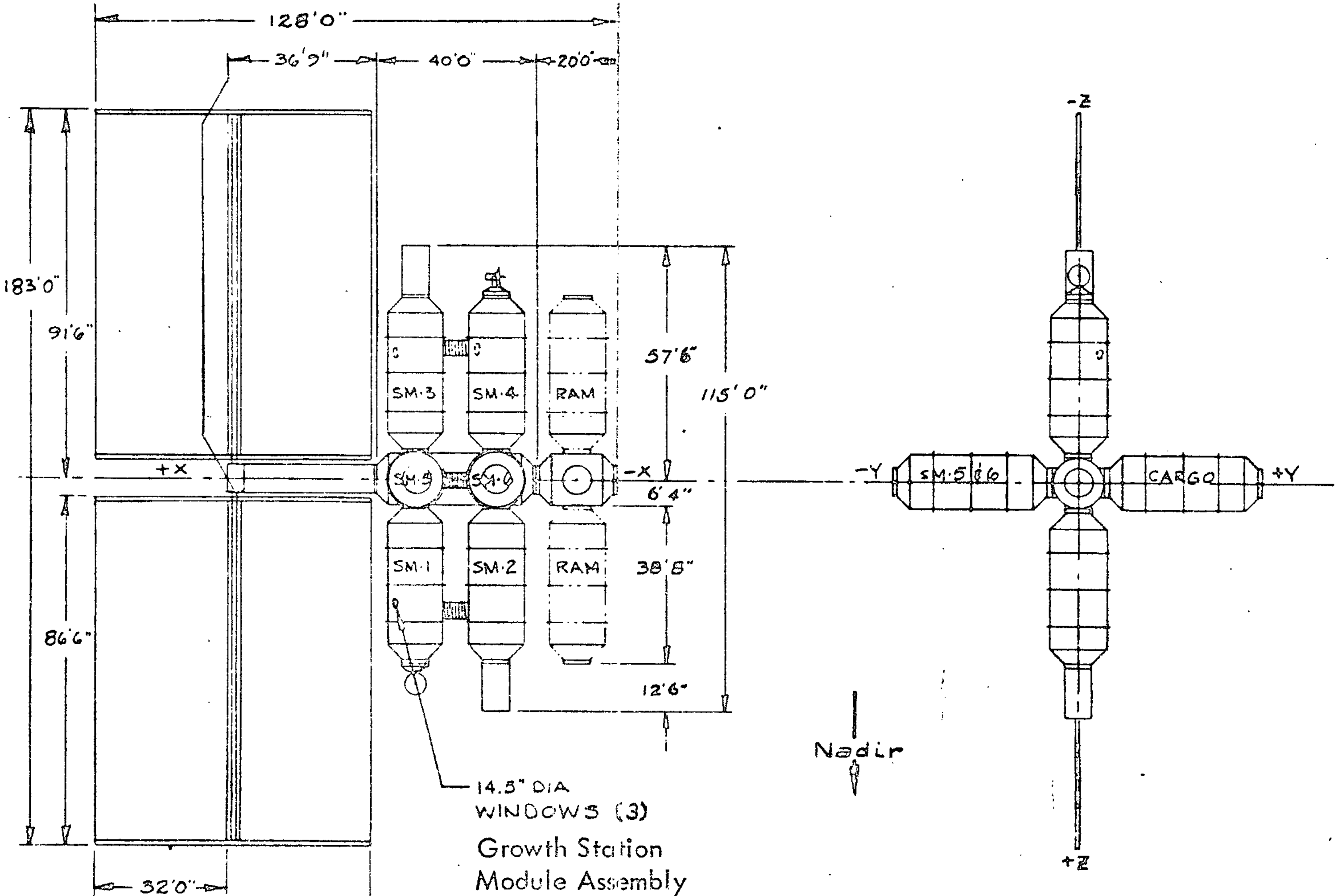


FIGURE B-2
040A SHUTTLE OVERALL CONFIGURATION



Initial Station
Module Assembly
North American Rockwell
7-9-71

FIGURE B-3.
REFERENCE SPACE STATION CONFIGURATION (EARLY VERSION)



Growth Station
Module Assembly
North American Rockwell
7-9-71

FIGURE B-4,
REFERENCE SPACE STATION CONFIGURATION (GROWTH VERSION)

0132-10046

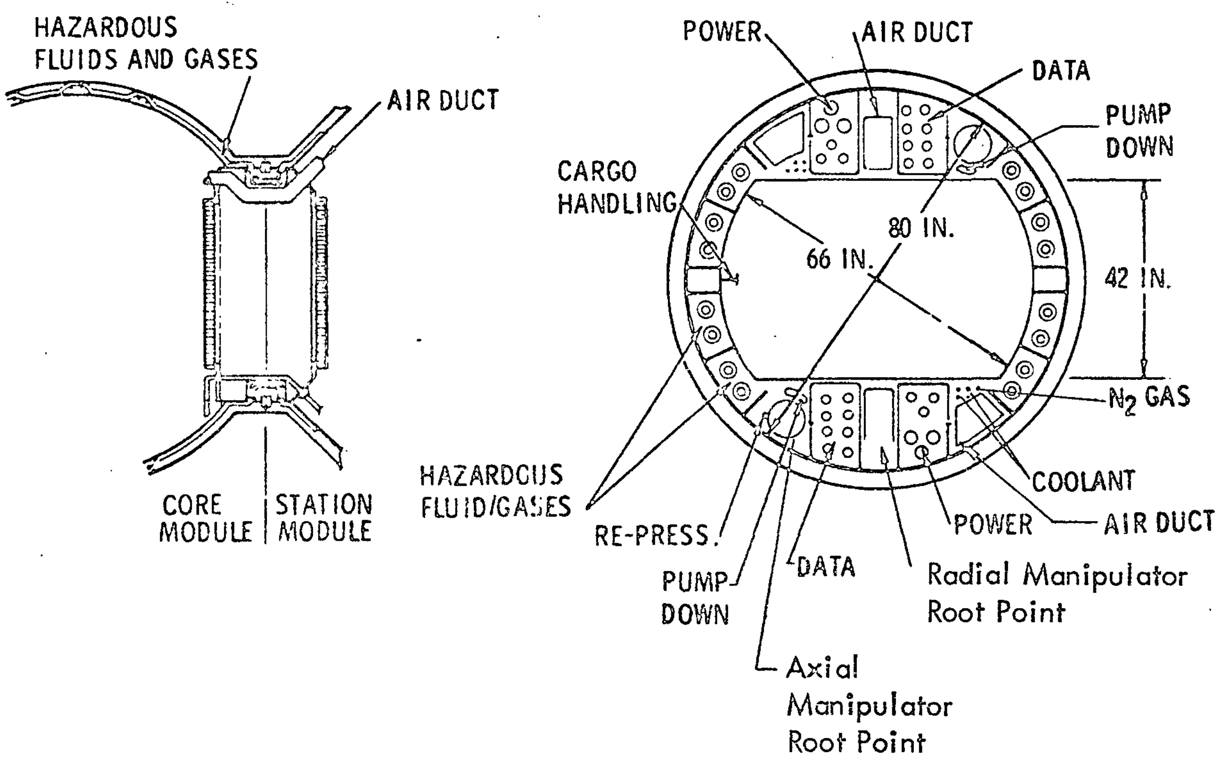


FIGURE B-5.
REFERENCE BERTHING PORT CONFIGURATION