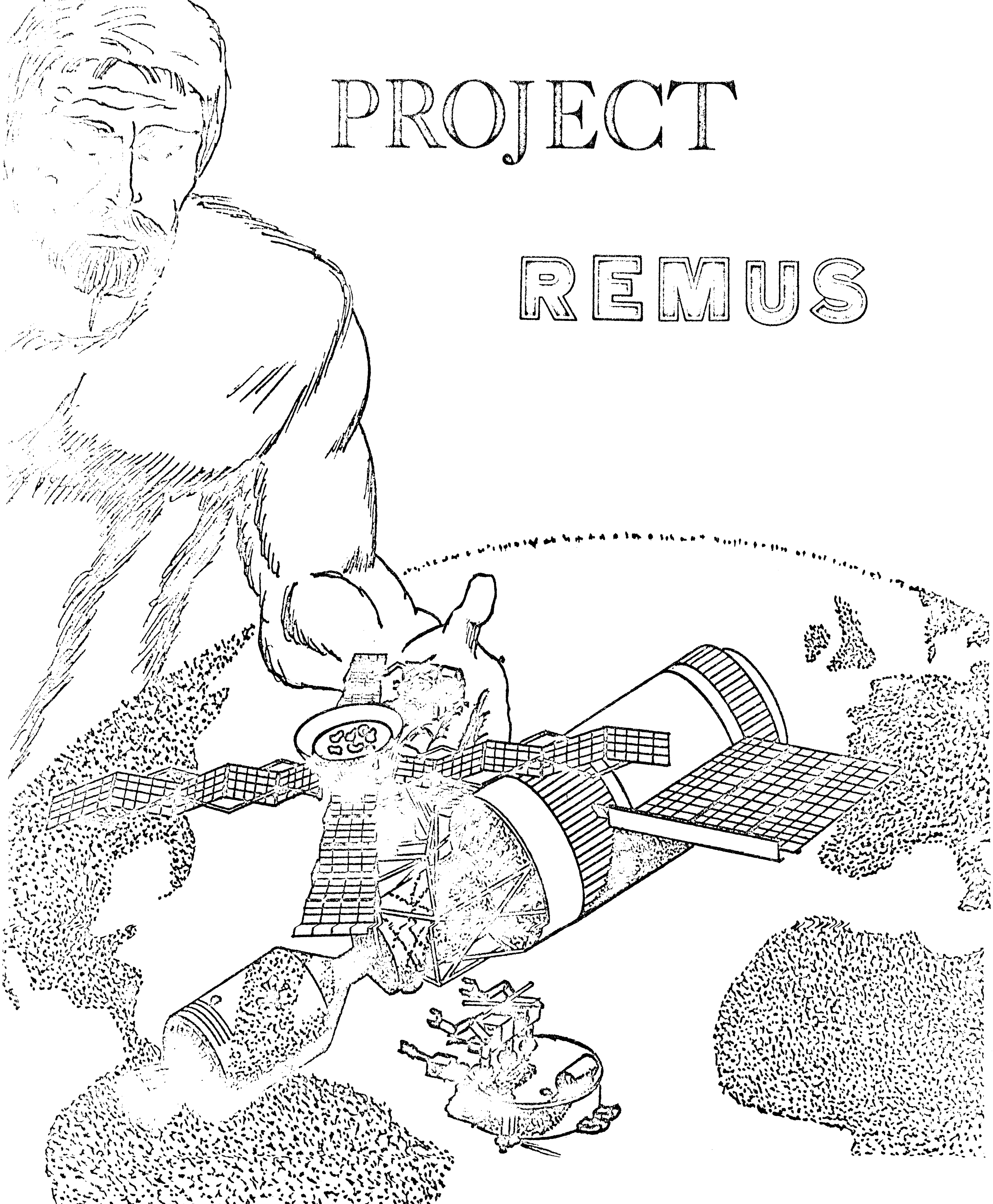
PROJECT REMUS



December 1970

9 December 1970

THE UNIVERSITY OF MICHIGAN
Department of Aerospace Engineering

PROJECT REMUS

PLACE:	Chrysler Center, Main Auditorium
DATE:	Wednesday, 9 December 1970
TIME:	1900 - 2230 hrs (7:00 - 10:30 PM)

Opening Remarks - Professor Wilbur C. Nelson

Introduction - Alan R. Dohner, Project Manager

Manipulators - Paul C. Mayer

Video - Edward C. Redmer
Kaywin A. Goodman

Attitude Control - V. Robert Denham

Intermission - approximately 15 minutes

Communications - David A. Leonard
William B. Dibble

Power - Michael F. Mitoma

Thermal - James M. Kevra

Structures - James C. Paul

Conclusion - Alan R. Dohner

Coffee Break - approximately 10 minutes

Questions and Discussion

ABSTRACT

Project REMUS is a preliminary design proposal for a remote manipulator system to operate around Skylab (SIVB) in 1976. The purpose of Project REMUS is to provide a human substitute outside the Skylab and eliminate dangerous extravehicular activity (EVA) for the astronaut. Project REMUS will also be used to explore the potential of a remote manipulator system for future space station and space base applications.

Project REMUS is designed to be completely compatible with Skylab and entirely reliable. Reliability is obtained through extensive testing and at least two and usually more levels of redundancy in components where failures might occur.

With the "ideal" Teleoperator system it would be possible for the operator to think he is at the worksite performing the task directly. It is our goal to give the operator the most complete link possible to the Teleoperator.

The Teleoperator is composed of seven different subsystems:

1. Manipulators
2. Video
3. Attitude Control
4. Communication
5. Power
6. Thermal
7. Structure

The manipulators are the astronauts hands and arms at the worksite. Force-feedback has been incorporated into the system to let the operator feel what the manipulator hand is touching. Three television cameras will provide a video link back to the console inside Skylab. Two of the three cameras will be mounted just above the arms to create the human effect of looking down over the arms. These two cameras will be used to produce a stereo effect for depth perception during docking. The third camera is on a tether and can be positioned to give an overview of the work area. Attitude control will be referenced to Skylab and determination of attitude will be done with rate gyros and rate integrating gyros. Attitude corrections will be made with reaction wheels and cold gas thrusters. Communications will be transmitting two television signals, manipulator commands and housekeeping telemetry. The power is supplied by rechargeable silver-cadmium batteries. Thermal control is maintained for the most part by passive means, however heaters are used during inactive period and for the extremely temperature sensitive gyros. The basic structure is shown in Figure 1.1.

Aero 483 - Spacecraft System Design - Course Background

Project REMUS is the twelfth in a series of preliminary design feasibility studies conducted in Aerospace Engineering 483. Previous studies have included a Mars probe, Jupiter probe, solar probe, polar-orbiting meteorological and earth resources satellites, a geostationary communications satellite for South America, a lunar far-side communication satellite, and a North Atlantic air navigation and communication satellite.

In this senior elective course, over a period of fifteen weeks, the students develop a preliminary design based on a problem statement with specific constraints. In the current problem a Teleoperator system for SKYLAB "B" (1975) was specified. The interplay between sensors, control, communications, power, weight and volume, etc., was then investigated and the Teleoperator configuration determined.

The students set up their project organization and meet two afternoons a week as a team and during weekends as sub-groups to coordinate the critical interface problems. Primary emphasis is placed upon team effort with a high degree of mutual interdependence.

Guest lectures are given by the faculty, university research specialists, industry and government specialists, and supplemented with small group conferences. The student is given the opportunity to apply his previous theoretical and analytical course work to the highly redundant field of preliminary design. He is also in active contact with professional experts in the field. Despite the short time available, it has been found possible to select current problems of national interest and make significant contributions. Copies of the final report are distributed to industry and government for review and comment.

Your comments are invited.

Wilbur C. Nelson
Professor
Department of Aerospace Eng.
The University of Michigan

12/9/70

Permanent comments which will be retained by Professor W. C. Nelson to help evaluate the project (to be turned over to Professor Nelson at your convenience).

(Name) ______________________ (Organization) ______________________

Date ________________

Questions and comments which will be used in the Discussion Period following the presentation.

(Name) ______________________ (Organization) ______________________

Date ________________

PROJECT REMUS

REmote Manipulators for Use in Space

In Roman Mythology, Romulus and Remus were the twins that founded Rome. In the space program Remus will be an essential part of man's beginning in an orbiting laboratory - Skylab (SIVB).

A Student Design Project
Department of Aerospace Engineering
The University of Michigan
Fall Term 1970

ABSTRACT

Project REMUS is a preliminary design proposal for a remote manipulator system to operate around Skylab (SIVB) in 1976. The purpose of Project REMUS is to provide a human substitute outside the Skylab and eliminate dangerous extravehicular activity (EVA) for the astronaut. Project REMUS will also be used to explore the potential of a remote manipulator system for future space station and space base applications.

Project REMUS is designed to be completely compatible with Skylab and entirely reliable. Reliability is obtained through extensive testing and at least two and usually more levels of redundancy in components where failures might occur.

With the "ideal" Teleoperator system it would be possible for the operator to think he is at the worksite performing the task directly. It is our goal to give the operator the most complete link possible to the Teleoperator.

The Teleoperator is composed of seven different subsystems:

1. Manipulators
2. Video
3. Attitude Control
4. Communication
5. Power
6. Thermal
7. Structure

The manipulators are the astronauts hands and arms at the worksite. Force-feedback has been incorporated into the system to let the operator feel what the manipulator hand is touching. Three television cameras will provide a video link back to the console inside Skylab. Two of the three cameras will be mounted just above the arms to create the human effect of looking down over the arms. These two cameras will be used to produce a stereo effect for depth perception during docking. The third camera is on a tether and can be positioned to give an overview of the work area. Attitude control will be referenced to Skylab and determination of attitude will be done with rate gyros and rate integrating gyros. Attitude corrections will be made with reaction wheels and cold gas thrusters. Communications will be transmitting two television signals, manipulator commands and housekeeping telemetry. The power is supplied by rechargeable silver-cadmium batteries. Thermal control is maintained for the most part by passive means, however heaters are used during inactive period and for the extremely temperature sensitive gyros. The basic structure is shown in Figure 1.1.

TABLE OF CONTENTS

1
INTRODUCTION

1.1 THE NEED FOR A REMOTE MANIPULATOR SATELLITE SYSTEM

For the last ten years man has been engaged in his first step of space exploration (i.e. achieving earth orbit and lunar orbit and lunar landing). In 1972 he will start his second step with the launch of the first Skylab beginning a series of space stations designed to provide a long term living and working environment in space. With these long term missions will come many extravehicular tasks. These tasks create at least two very undesirable problems which would not exist with our remote manipulator satellite.

The first problem is that of astronaut safety. Anytime an astronaut goes EVA he is particularly vulnerable to accident. His space suit is the only thing between him and a complete vacuum, any cut or puncture would be fatal. He is supplied with oxygen through an umbilical hose which adds another dimension of vulnerability. The exposure of the astronaut to such danger is strenuous, both mentally and physically, causing him to fatigue rapidly and making the situation even worse. With a remote manipulator the problem of astronaut safety does not exist because the astronaut is inside the Skylab.

The second undesirable aspect of astronaut EVA is that it is so strenuous that when an EVA task is scheduled the astronaut does nothing else that day. Also for safety reasons one astronaut never goes out alone. This means two man-days are used for any EVA tasks and since there are only three astronauts on the Skylab this has a crippling effect. However with the remote manipulator only one astronaut is kept busy for only the duration of the particular mission, resulting in the saving of at least one man-day.

1.2 DESIGN PHILOSOPHY

Project REMUS is a preliminary design proposal for a remote manipulator system to operate around Skylab (SIVB). The Satellite with the manipulator arms and support systems will be referred to as the Teleoperator and the whole configuration as the remote manipulator system or Project REMUS.

The following constraints have been placed on the system:

1. State-of-the-art technology
2. Compatibility with Skylab (SIVB)
3. Complete reliability
4. One year life cycle
5. Stereo television
6. Two manipulator arms (three docking tethers)

Project REMUS will perform two specific missions on Skylab (SIVB). The first is film retrieval and replacement from the Apollo Telescope Mount (ATM). The second is an inspection flight around the outside of Skylab. Both these missions will be discussed in more detail later in the report.

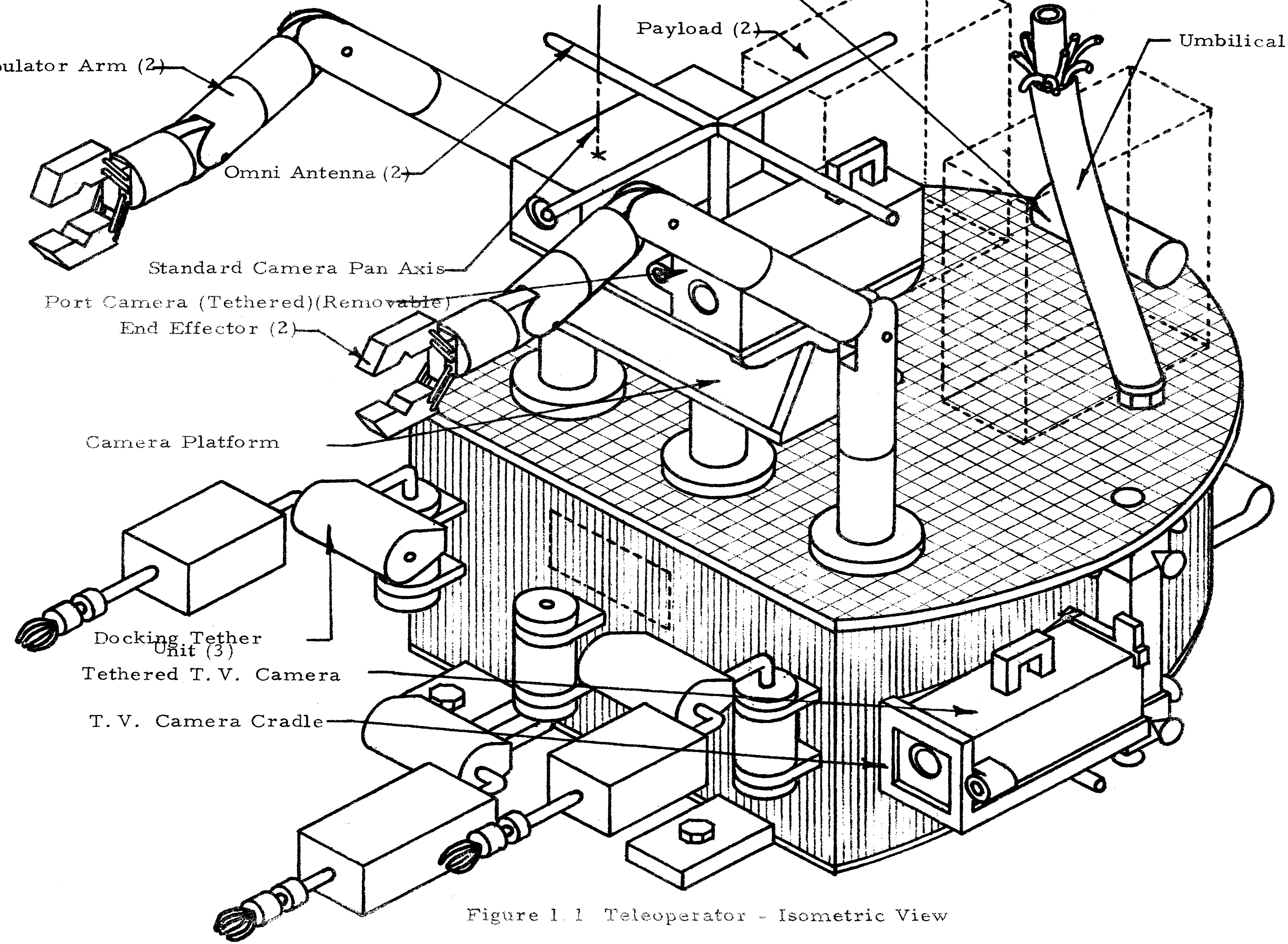


Figure 1.1 Teleoperator - Isometric View

2
MANIPULATORS

2.1 INTRODUCTION

REMUS is an independent system whose purpose is to eliminate astronaut EVA during the flight of Skylab B. The requirement of the manipulator subsystem is to perform all tasks now required by one or more of the astronauts due to make up the crew of Skylab. Each section of the manipulator subsystem will be discussed in detail with diagrams when appropriate.

2.2 TASK DESCRIPTION AND REQUIREMENTS

During the planned 56 day flight, the crew of Skylab will be required to perform one of the following tasks on the day scheduled.

Task	Day	
ATM film installation	3	
ATM film exchange	26	
ATM film retrieval	54	(day and frequency subject to change)

In developing a manipulator system, all of the above tasks must be designed for. Enough flexibility must also be built into the system to perform tasks not previously scheduled, i.e. emergency repair, inspection of the exterior of Skylab, deployment of experimental packages, etc. Using the EVA tasks from Skylab A as a guideline, the ATM film missions were analyzed in detail. In addition to these, capabilities were also added to perform the two additional tasks; D021-deployment of astronaut expandable airlock, and D021/24-retrieval of two panels containing thermal coating samples and samples of the airlock materials. Although these two may be completed on Skylab A, if similar experiments are included on Skylab B, the manipulators will be capable of performing them.

Each film mission is divided into two steps, each consisting of replacing the appropriate number of film packages and cameras in a separate section of the Apollo Telescope Mount (ATM) canister. The Center Work Station (CWS) receives three film magazines and one camera already filled with film. The Sun-End Work Station (SEWS) will receive two film magazines, each containing film and camera. Each of the experiments, with its location and film data, is listed in Section 1 in Appendix A on page 105.

All forces needed to open or close access doors or remove film magazines will not exceed 10 lbs as per sheet D-10 of 10M32158 for astronaut EVA requirements set by NASA and supplied by Martin Co., Denver, Colorado. All latches will be redesigned to be operated by the end effector of the manipulators. A minimum of 2.0" of clearance will be provided for camera and film magazine removal.

In order to study the tasks, a procedure was set up, describing each step in detail.

INITIAL CONDITIONS: The Teleoperator is located at the Airlock Module (AM) external workstation located in the EVA bay. The CWS and SEWS film magazines are attached to their respective film trees and located in brackets just inside the AM hatch.

1. Confirm condition go.
2. Transfer CWS tree from AM hatch and place in bracket on rear bed of teleoperator.
3. Verify by vision that stowage latch is secure.
4. Transfer SEWS tree through hatch and place it in its AM external temporary location.
5. Verify stowage latch secure.
6. Teleoperator translates to ATM CWS.
7. Initiate docking position by extending and positioning docking tethers.
8. Complete docking by locking on astronaut handrails.
9. Go through switching procedure for CWS control panel to provide power, to release launch safety clamps, and to rotate ATM canister.
10. Remove S-054 film magazine from film tree (exchange or retrieval).
11. Rotate ATM canister to S-054 film access door.
12. Open S-054 film access door.
13. Remove S-054 film magazine from inside ATM canister (only for exchange and removal).
14. Replace with new S-054 film magazine.
15. Place old film magazine on film tree at rear of Teleoperator.
16. Close access door for S-054.

17-37. Repeat steps 10-16 for the remaining experiment in the following order: S-056, S-052, H-alpha No. 1.

38. Verify that all film magazines are secured on film tree. Lock canister to prevent further rotation.
39. Undock and translate to AM external workstation.
40. Remove CWS film tree and place in its AM external temporary location.
41. Remove the SEWS tree from its temporary storage position.
42. Place in bracket on rear of Teleoperator and verify that it's secure.
43. Teleoperator translates to SEWS at ATM.

44. Initiate docking and lock to tether holds.
45. Open the NRL-A canister door, located on film tree.
46. Remove NRL-A film magazine from NRL-A canister.
47. Open the NRL-A film access door, located on ATM.
48. Remove NRL-A film magazine from access door in ATM.
49. Replace new RNL-A film magazine in ATM.
50. Close access door after verifying installation.
51. Place old NRL-A film magazine in canister on film tree located at rear of Teleoperator.

52-58. Repeat steps 45-51 for the NRL-B magazine removal/replacement.

59. Verify that film canisters are secure on film tree.
60. Undock and translate to CWS.
61. Dock and unlock ATM canister.
62. Undock and translate to AM external workstation.
63. Remove SEWS film tree from Teleoperator and transfer through AM hatch and secure it in its AM internal storage location.
64. Remove CWS film tree from its temporary location and transfer through AM hatch and secure it in its AM internal storage location.
65. Secure AM hatch.

The design of the entire manipulator system and related subsystems has been accomplished with these procedures and tasks in mind.

There are several definite advantages in using the Teleoperator instead of one or more astronauts to perform these EVA tasks.

Presently, these tasks will take the astronauts about 146 minutes total. This however, does not include the 160 minutes needed to prepare for EVA and to stow equipment after the EVA is completed. This adds up to well over 300 minutes or about 5 hours. Besides this time, it has been the rule that no other tasks will be performed on the same day as EVA. This means that an entire day would be wasted. With REMUS, the task will take about 210 minutes, but would require less preparation and shut down time. Also, once the task was completed, the astronaut could perform other tasks since he could rest at any time during the task and would not become as fatigued.

The tasks outlined here would take two astronauts and would confine the third to the command module. By using REMUS, it would require only one astronaut and the others would not be confined.

Less equipment would be required since no EVA would be necessary. This would include things like tethers, umbilicals, and possibly even EVA suits. Precious things like water and oxygen would be used less often if the EVA were eliminated.

By using REMUS instead of EVA, the biggest advantage is the safety aspect. The astronaut would not have to perform the dangerous task of walking in the space environment where the smallest tear or mistake could mean his death. If, for no other reason, this system should be used on Skylab.

The requirements and design for the manipulator subsystem of REMUS are discussed in detail in the following sections.

2.3 MANIPULATOR SYSTEM DESCRIPTION

The manipulator subsystem of the Teleoperator will consist of two compact, bilateral, six-degree-of-freedom manipulators with force feedback, three motorized tethers, master control console, and related subsystem requirements. Each of these have been analyzed in light of the tasks as well as with an eye on future applications.

The manipulators will consist of a master-slave configuration capable of imitating the motion of the human arm. A single arm will be made up of a shoulder joint, an upper arm, an elbow joint, a lower arm or forearm, a wrist joint, and an end effector. Each arm will have a 40" reach with a nominal 32" working area. Each will have a force capacity ranging from 8 lbs with the army fully extended to an optimum of 320 lbs. Calculations are in Section 2.1, Appendix A. The shoulder, elbow and wrist joint will fold to a minimum included angle of 40^{o}. The force capacity and folding limitations exceed that of the human arm and is adequate to perform tasks originally designed for astronaut EVA. If force multiplication is necessary, this can be implemented by using a diode network in the control circuit, incorporating "bad" diodes. This could provide up to a 5:1 force ratio.

The arms will be positioned 26 inches apart, and 18 inches above the Teleoperator bed. The cameras will be placed 6 inches above the shoulder joints to imitate the same relation as would a "head" on the operator.

The familiar counterbalancing found on hot lab mechanical arm units will not be necessary in the space environment. With this type of design, with the servo motors at the joint, counterbalancing is very difficult. This problem will have to be overcome for the purpose of testing the system in the earth's gravitational field. This report will not deal with this problem in detail.

For the tasks outlined above, the film trees designed for astronaut use will be used by the Teleoperator for the film magazine transfer. These trees will be clamped into brackets located on the rear bed of the Teleoperator. All of the steps in the film transfer can be accomplished with a single arm. This makes each of the arms a back-up system for the other. Since a single arm has its own power, communications and control, it can be operated independently of the other and can function if the other arm should fail. These missions require no special tools in order to perform them. A design has been developed to attach a "tool box" to the Teleoperator if the need arises during an emergency to perform maintenance on external structure of the Skylab. This tool box would snap on the front of the Teleoperator and would contain tools, spare parts, and storage for parts that are replaced. This tool box would be passed through the AM hatch to the Teleoperator when the need arose.

A tentative duty cycle has been established for the arms, using studies done by General Electric and by Mr. Carl Flatau of Brookhaven National Lab and the speculation of this group. This figure has not been finalized but is near 25%.

All the joints will be equipped with force feedback with a one ounce touch capability. This can be varied if tests should prove that finer touch capabilities are necessary.

The arms will have a standard configuration for storage and docking. This configuration can be seen in Figure 8.10, on page 97 . This mode will always be used when the arms are not in operation. This will occur during all phases of docking and while being recharged at its permanent station. Also during its actual flight from the OWS to the CWS and SEWS, the arms will be locked in this position in order to be stabilized for easier attitude and control operations. This figure also shows the relation of the cameras to the arms, as well as the tethers.

Inertia and speed calculations for the arms appear in Section 2.2, Appendix A.

Many problems were encountered in the design of this system. These have been outlined and discussed in Section 5, Appendix A.

2.3.1 Manipulator Arms

There are two types of joints on each arm. The first type, shown in Figure 2.1 produces a "scissor" action between two members. The second type, as in Figure 2.2, results in a concentric motion with the members having a common axis of rotation. Figure 2.3 shows the motions of each joint in the arm.

The peak torque of the Model 301 Micro Switch motors used in all joints is 32 oz-in. All motors are equipped with electric heaters to prevent freezing or sluggish response when the arms have been inactive while in the

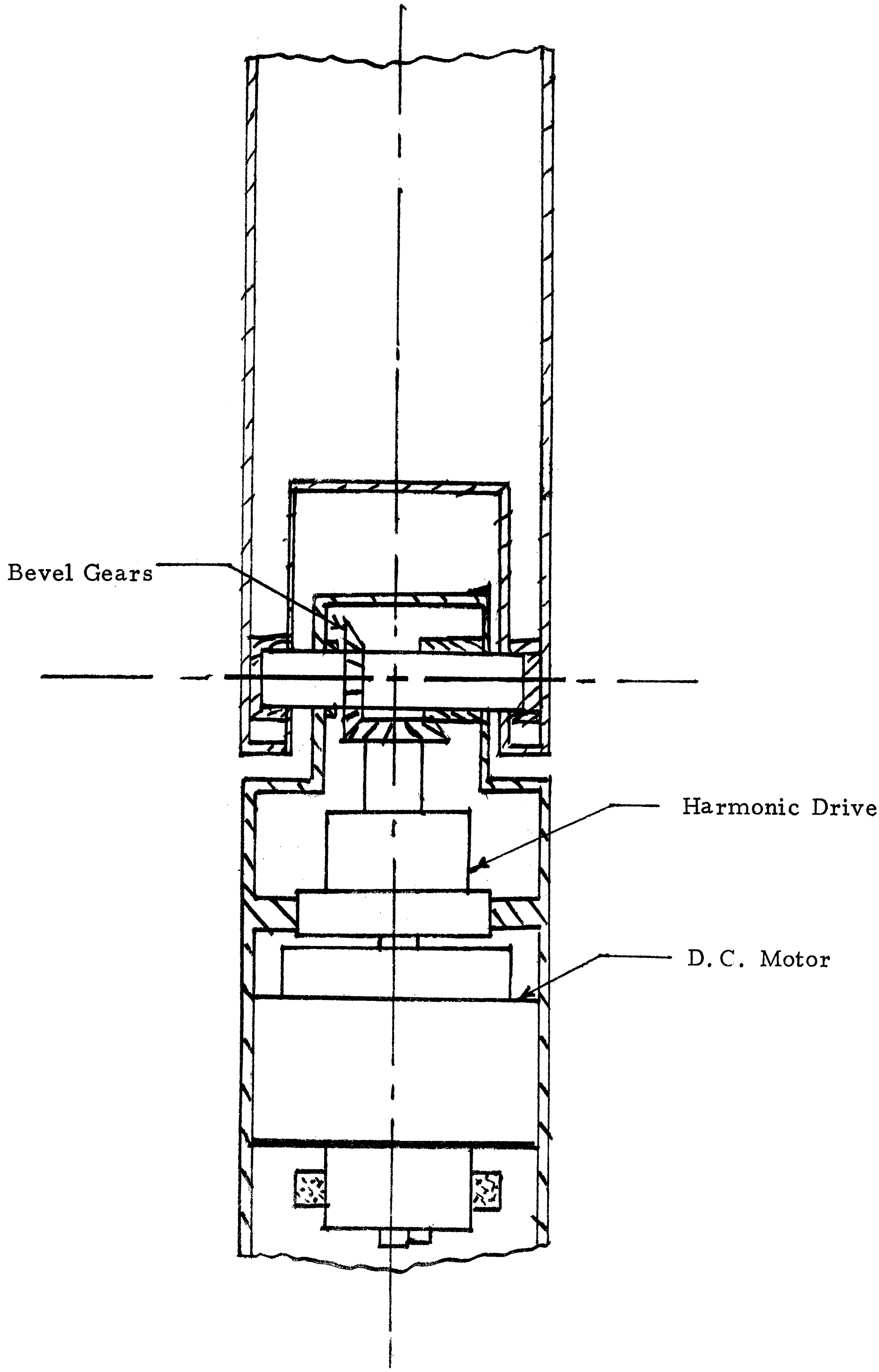


Figure No. 2.1 Scissor Motion Joint

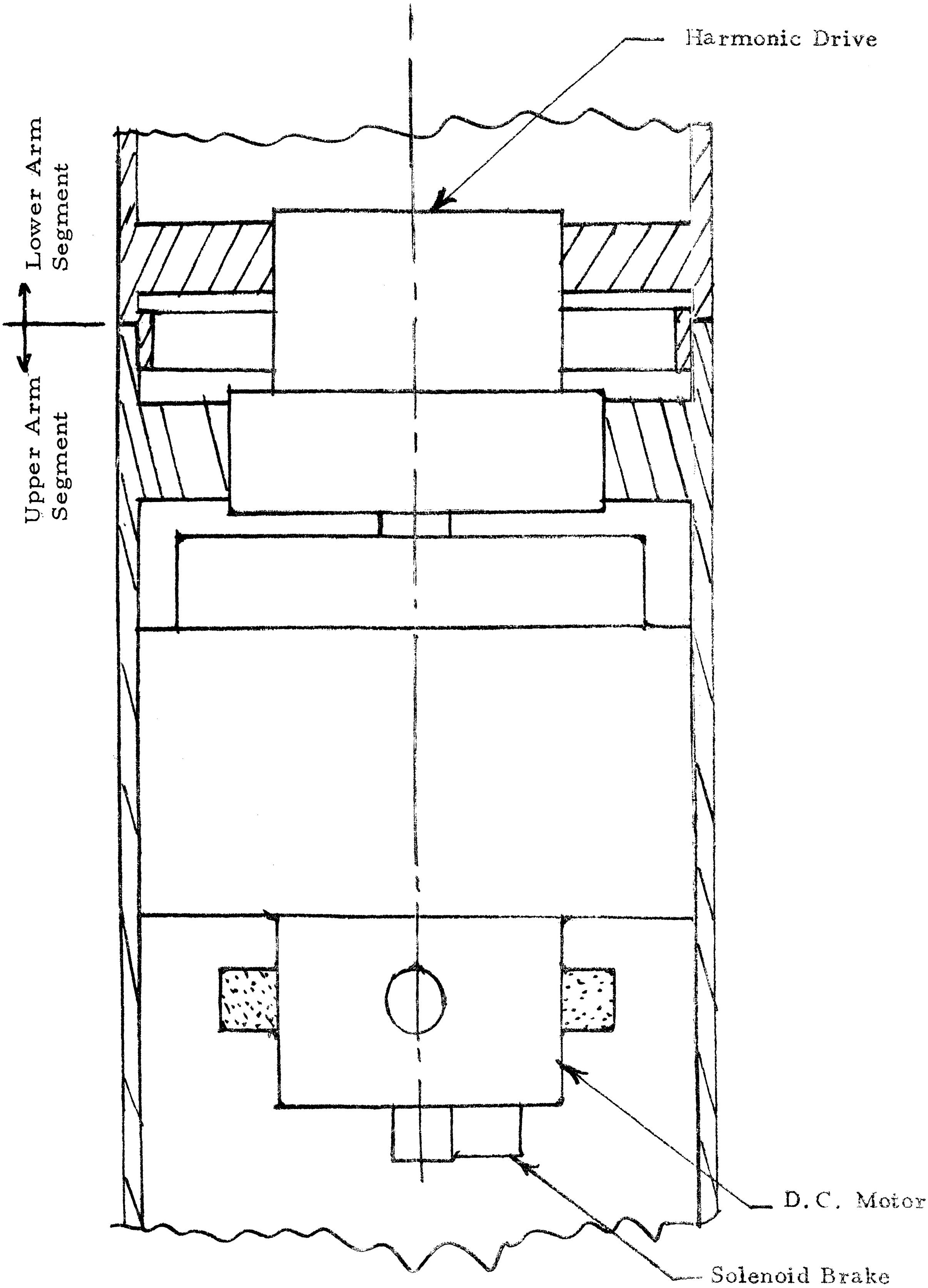


Figure 2.2 Concentric Motion Joint

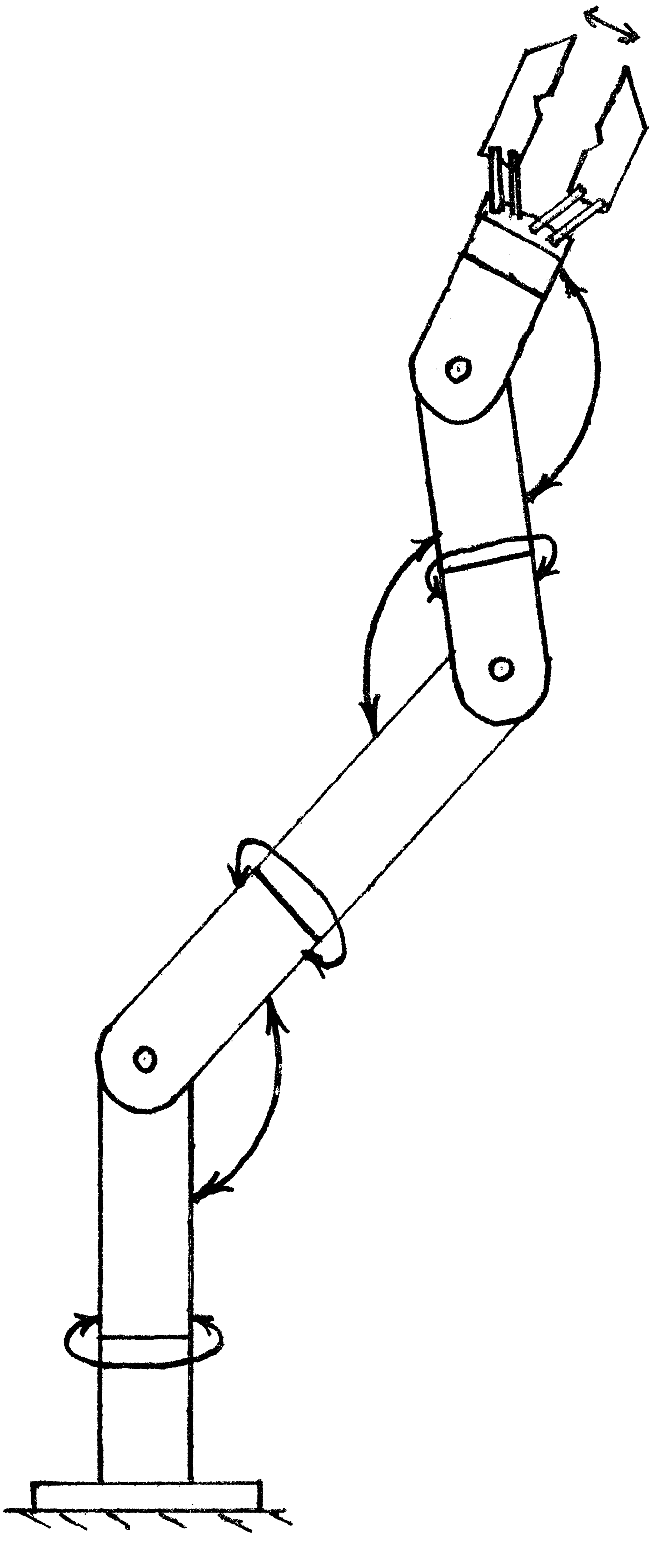


Figure 2. 3 Joint Motions of an Arm

shade. Each joint has a solenoid brake on its motor as a safety measure. The motors are equipped with special vents for forced cooling by the helium in the hermetically sealed arm segments.

Harmonic drive actuators are used for speed reduction and torque amplification in each joint. The Flexsplines of the drive are made of steel rather than plastic because of better temperature range. The model specified is HDC-3C-160-2, Model C. It has a reduction of 160:1 and it is lubricated with ANDOK-D grease prior to installation in the arms. The harmonic drive in the master and the slave are 90 degrees out of phase to average the friction.

It is necessary to hermetically seal the arms to accomplish heat conduction from the motor rotors efficiently. Another reason is so that the potentiometer in each joint will operate, as they will not work in a vacuum. The potentiometer readings will be fed through the computer aboard Skylab to avoid possible ambiguity.

The two types of joints are basically the same. The only difference is that the first type has two bevel gears to change the axis of rotation to produce the scissor action between the members. The gears, of course, are not necessary in the second type of joint since the relative motion of the members is about the same axis.

The end-effector has an Inland D. C. Torque Motor, Model T-1218. Peak torque is 15 oz-in. Reduction is via a gearbox and positioning by potentiometer.

A special joint in the slave for indexing was made unnecessary by placing two potentiometers in the shoulder joint of the master. Only one potentiometer is used at a time. When the operator wishes to index from his present position, he presets the second potentiometer to be out of phase with the first potentiometer by X degrees. He then switches from the first to the second potentiometer. While he remains still, the slave gets an error signal of X degrees and moves to make the error zero, and thereby attains the desired indexed mode. The controls for setting the second potentiometer and switching to it are on the Console.

The master arms are of the exoskeleton type. The exoskeleton design is superior to the conventional master because it allows the operation to perform more naturally and therefore with greater ease and efficiency. In the event a suitable exoskeleton is not developed in time for Skylab the conventional master arms can be substituted without significant modification to the system.

2.3.2 Force Feedback

Incorporation of the servo motors in the arms results in inertias that are higher than desirable. In order to improve the response, the reflected friction and inertia levels must be reduced. The servo scheme that is used will allow this type of design and still reduce the effective frictional and inertial forces reflected to the master.

The simplest scheme turns out to be the position-force system shown in Figure 2.4. As in all bilateral-force reflecting manipulators, both the master and slave must be driven from transducer information. Previously, both units were driven from the same position error but in opposite directions. As can be seen, only the slave arm is driven by position error while the master arm is driven by torque error due to comparison of a separate set of torque transducers. All transducers are always placed at the very output of the motion. This system is more complex, but this is outweighed by the fact that all friction and inertia forces of both the master and the slave are divided by the force loop gain before being reflected at the master. This effect substantially cancels the forces mentioned above.

Besides the obvious advantage mentioned above, force feedback is used for other reasons. Since the Teleoperator is an independent satellite, that is, separated from the control by space, there are no mechanical means of transferring a force encountered by the slave arm back to the master arm. This may not be necessary because of the slow motion of the arms and the visual coverage of two cameras. However, no matter how slowly the slave is moved, or how fine and accurate the video system is, the master unit still lacks the "sense of touch". Consequently, the time to do a job is more without some type of touch sense. Experiments conducted by General Electric, among others, have shown that the average times for the performance of simple tasks were increased substantially when no touch capabilities were present as compared with a force feedback system. Besides the shorter task time, there is the possibility of damaging the manipulator as well as some part of the object being worked on when none of the forces exerted by the slave are "felt" by the operator. Video would tell the operator of a collision, but could not inform him of how hard he had hit the object.

The idea of force feedback is simple in theory but difficult to implement efficiently. This servo scheme has been found to be the best to this date, but like all branches of technology, it needs refining.

The failsafe circuit shown acts as a safety device for two types of failure. It monitors position error and if instability occurs in the system, the solenoid releases the brake and the motor is locked. It also monitors any electrical

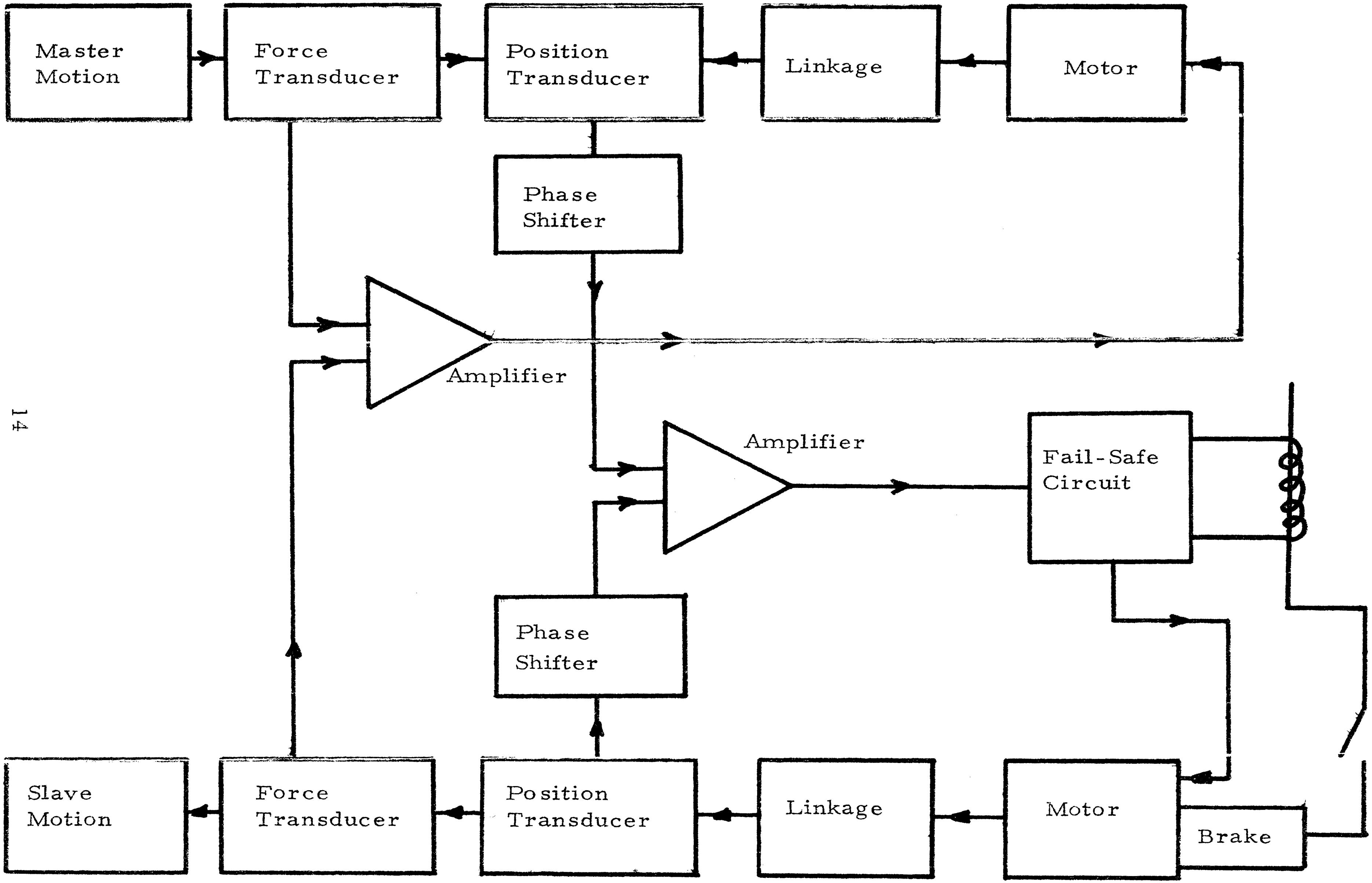


Figure 2.4 Position-Force Servo System (One Master-Slave Link)

failure that may occur in the circuits. The position error signal will be monitored in Skylab on the control panel including a reset switch if the failure is cured.

Back-ups for this system are simple. By putting in a few redundant circuits, the manipulators can still operate if either the position or the torque transudcers should fail. By supplying 3 extra amplifiers and redundant circuits for switching, amplifier failure can be backed up.

The actual components for this system are fairly simple except for the torque transducers. These consist of a folded, low-hysteresis steel arm equipped with a full four-arm strain-gauge bridge. The strain gauges are of the solid state type. The entire combination forms a sensitive, temperature stable, low-hysteresis torque transducer with a dynamic range in excess of 1000:1 and unamplified full scale output of about 2 volts. This was designed by Mr. Flatau with some sacrifice of linearity.

The position transducers are single turn, conductive plastic potentiometers capable of continuous mechanical rotation. The communications require that all signals be unipole, from 0-5 volts. The amplifiers are used only to convert the bipole voltage outputs of the transducers to unipole signals for the communications equipment. Slight voltage amplification may be needed and more development is needed in this area. Presently, the entire 17 amplifiers should take up about 1 cubic foot of space within the base of the Teleoperator.

With the arm and force feedback design in mind, the end effector is the next area to be considered.

2.3.3 End Effector

Although the human hand has twenty-two degrees of freedom, all the tasks that must be performed by the manipulators can be accomplished with just one degree of freedom. The end effector that will be used is of the parallel jaw design with the following features.

a. The jaw pads will be removable in order to change texture. Hard, serrated, or pliable pads can be used if necessary.
b. The opening of the jaws will be from 0 to 6 inches and will be capable of gripping any outside structure on Skylab.
c. These jaws will also have an electric lock to maintain grip without draining power and stalling the motors.

The jaws will be of the design shown in Figure 2.5. The triangle opening formed when the jaws close will be able to accommodate the diameter of the handles on the film magazines. This opening may be lined with some material to provide a sure grip on these handles.

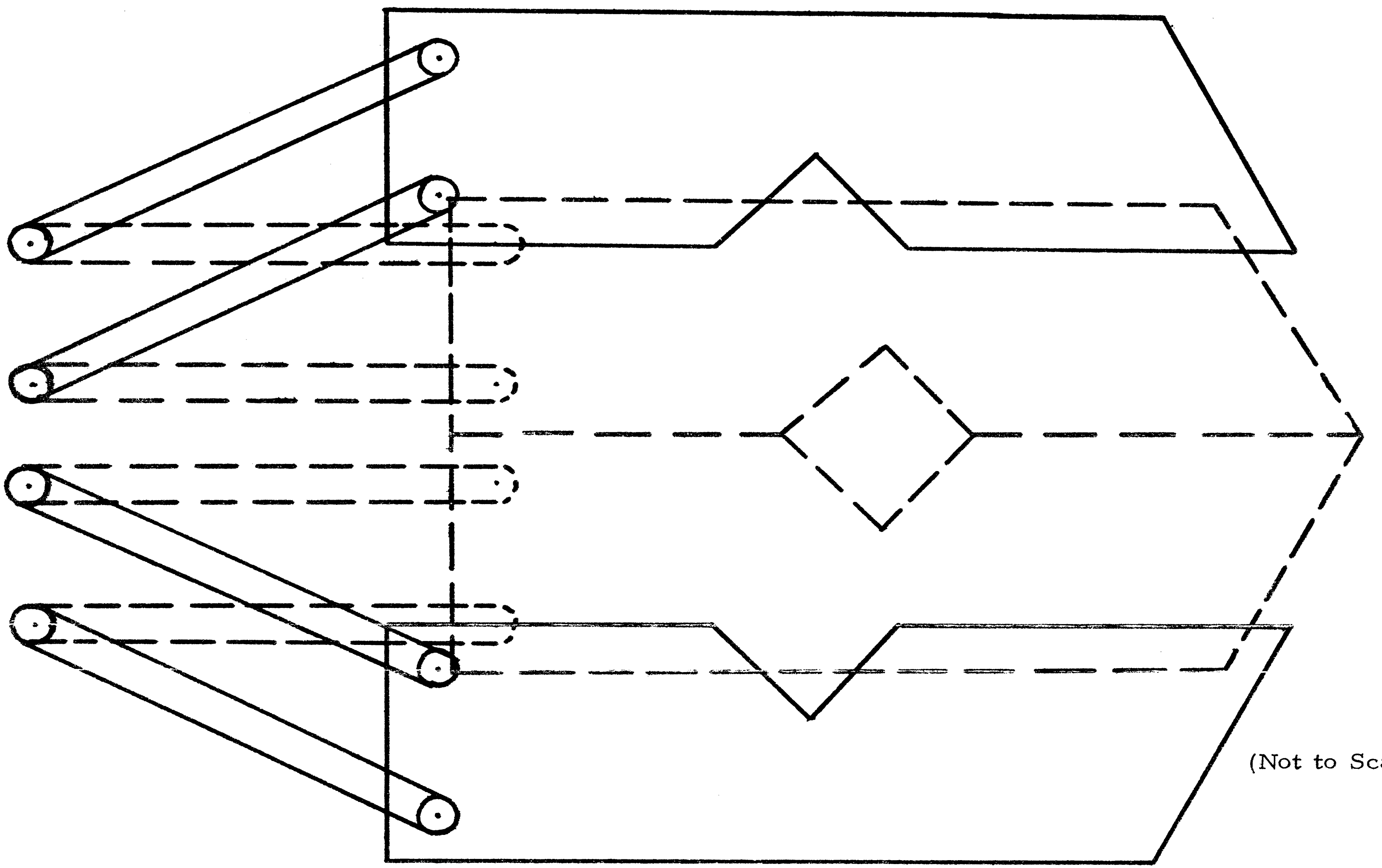


Figure 2.5 Parallel Jaw End Effector in Open and Closed Position

In the case where the wrist may double as a power tool, an end effector may be designed to snap on and off, thereby allowing socket-type tools to be snapped on the power "wrench". An alternative to this would be to design the tools to be gripped by the tongs before rotation.

If the Teleoperator is used for more delicate tasks than those outlined, another possible design would include touch sensors in the jaws themselves to act as a safety device. When one jaw touches an object with a predetermined amount of force, the jaw would stop closing until the opposite jaw felt the same amount of force and then it too would stop. The operator would then reset a switch and continue the operation. This would reduce the possibility of doing damage to the object being held. It would be switched off for other operations where the safety factor is not needed.

2.3.4 Fasteners

An analysis of the fasteners used on the containers, access doors and other similar objects, was done to determine if the end effector of the manipulator arm would have any difficulty in using them. Each different fastener was studied and evaluated.

Several handles located in spots like the airlock hatches were of a design that required a twist to the right to unlatch them. Because of astronaut use, the force requirement is less than 10 lbs and since the handle is round and can be gripped by the jaws of the end effector it was decided that this type of fastener could be operated by the manipulators.

A number of D-ring fasteners are used and these are of two basic designs. One of these must be pulled and the other must be twisted. Again, with the 10 lbs force requirement and the round handle it was decided these could be operated by the arms.

One of the launch locks on the CWS access door requires a simultaneous push and twist. Since the end effector can attain a secure grip on the handle, this motion can be performed by the manipulators.

Two of the fasteners found on the present Skylab design were found impossible to handle easily. One of these requires a trigger to be pulled and the other requires that a button be pushed while the handle is pulled. These will have to be changed to be used by the Teleoperator. Presently, General Electric has designed an end effector that is capable of pulling a trigger. This could be used, but would greatly complicate the design and the power requirements. It would be considerably easier to redesign the fastener. The second type of fastener could be remedied by two methods. This fastener occurs on the S-082 film magazines and is used to extend the film magazine handle as it is positioned in the ATM canister. The first method would be for the astronaut to deploy the handle before it is received by the Teleoperator. The second would be to redesign the handle. Either method would be suitable. This fastener could be operated as it is, if both hands could be used at the same time. Since the operating room within the access door is limited, this function would be very difficult to perform.

By designing the arms to closely imitate that of the astronaut doing the same task, the only problem encountered is that of the above two fasteners and these can be changed. In order to get the best design to perform the necessary requirements, all subsystems had to be analyzed to determine the requirements of the manipulators. The results of this analysis in the form of subsystem break-downs can be found in Appendix A, Section 3.

2.4 TETHERS

The main functions of the tethering system on the Teleoperator are 1) to aid in docking, and 2) to provide the necessary stability during task performances. Consequently, this system is very strong and rigid for stability purposes, as well as, maneuverable for docking.

The tethers will be located as shown in Figure 1.1 . Holds for the three tethers are provided both at the Center Workstation and at the Sun End Workstation of the ATM experiment package. The tether attachment at the workstations provides a very stable working configuration for the Teleoperator relative to the ATM.

A stability study, based on the maximum forces and torques exerted by the manipulator slave arms under working conditions, indicates that each tether must withstand a 100 lbf axial load. In addition, the two top tethers must withstand a bending moment of 15 ft lbs, while the lower tether must withstand 30 ft lbs bending moment. These criteria indicate that the tethering system be rigid. Calculations are located in Section 4, Appendix A.

On the other hand, the tethers must be "out of the way" during periods of time that the Teleoperator is operating free of a workstation. Also, the internal storage space needed for the tethers must be minimal for these time periods. However, since the tethers are used as docking aids, they must be readily deployable.

Due to the above mentioned operating conditions, the Teleoperator has been equipped with BI-STEM tethers. The STEM (Storable Tubular Extendible Member) theory has been developed by SPAR Aerospace Products Ltd. of

Canada and has many notable features. Basically, the STEM is a thin tape of metal on a motorized spool; as the tape is allowed to unwind from this spool, it assumes a tubular shape, the strength of which is determined by the type and thickness of metal used. The tubular shape allows the STEM to be very strong, and yet, considerably lightweight. The BI-STEM is simply a combination of two STEMS, resulting in an even stronger member.

Figure 2.5

Two BI-STEM systems are used on the Teleoperator; one is Model A-798 for each of the top tethers, and the other is Model A-631 for the lower tether. These are off-the-shelf models so it was necessary to make revisions of extension/retraction rates and length. Specifications for the systems used on Teleoperator are given in Table 2.4.1.

While the systems chosen provide considerable range and adequate strength, more flexibility has been built into the tethering system in that each tether can be pivoted horizontally and vertically. To accommodate this, two small 28 volt D.C. auto-braking motors are used at the base of each tether. One of these motors is mounted vertically and provides horizontal pivoting, and the other is mounted horizontally and provides vertical pivoting, (see Figure 2.6). A gear train linkage is used to reduce the rotational speed of the D.C. motor output shaft to .5 rev/min. These motors are hermetically sealed to insure that enough heat is dissipated so as to avoid overheating, and subsequent failure. However, if this should occur, the tethers can be

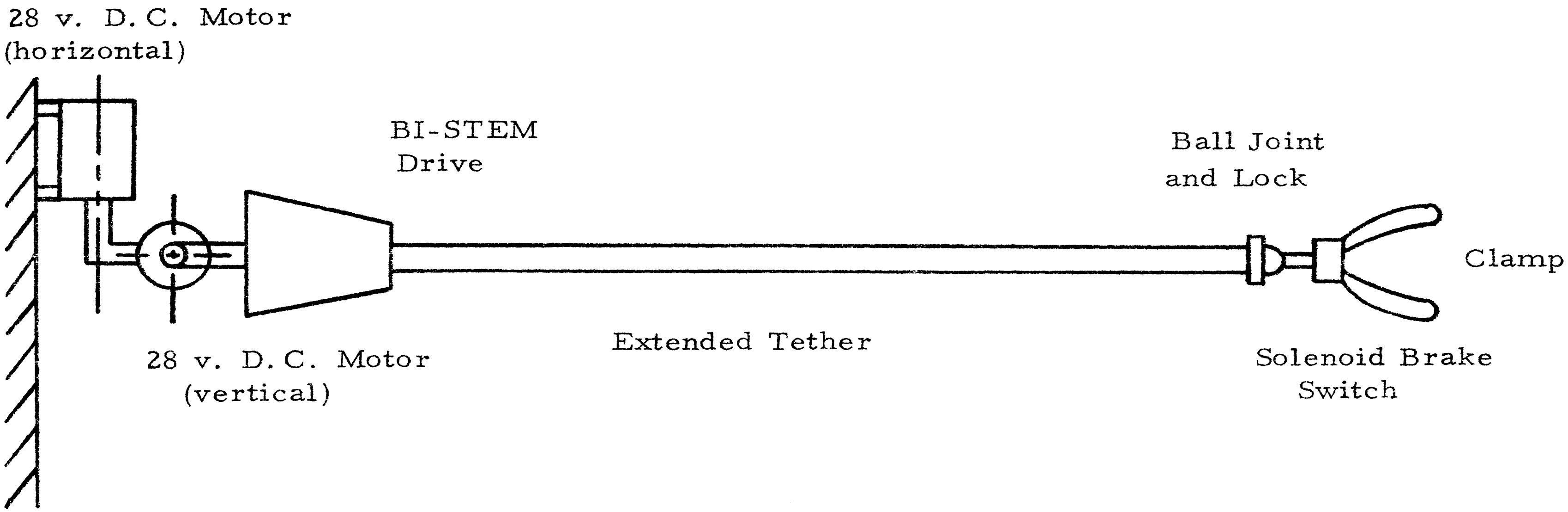


Figure 2.6 Tether Design

Table 2.4.1

Description	Model A-631	Model A-798
Material	Stainless Steel	Stainless Steel
Length	6 feet	6 feet
Element Diameter	1.34 inches	.75 inches
Thickness	.007 inches	.004 inches
Bending Moment	750 in lbs	250 in lbs
Size	5.2" x 5.3" x 11"	5.6" x 4.0" x 8.87"
Voltage	28 volts D.C.	28 volts D.C.
Power	20 watts	20 watts
Ext/Retraction Rate	1 in/sec	1 in/sec

positioned by the manipulator slave arms. Control of these motors is by the master console operator; therefore position potentiometers are used on the individual motor shafts in order that the operator may know the exact locations of the tethers relative to the horizontal and vertical axes.

At the extended end of each tether is a spring-loaded, three tonged clamp, which is mounted on an electrically locking ball joint. The purpose of this locking ball joint is to provide movement horizontally and/or vertically of the tether without the release of the clamp from the tether hold. The clamp is operated by a solenoid braking switch controlled by the master operator. When no current is flowing through this circuit, the clamp is closed, and vice versa. Hence, the clamp will be closed at all times except for a few moments during the docking period. The spring, therefore, is very stiff so as to provide the clamp with an extremely secure grip. This enables rigid attachment of the Teleoperator to the tether holds. The open spread of four inches of each clamp allows for small errors that could arise during the docking maneuver.

Since the tethers are completely operated from the master control console, several switches and indicators are located on the master panel. These components are:

1. One toggle switch for each tether (extension/retraction)
2. One toggle switch for each clamp (solenoid lock)
3. One toggle switch for each ball joint lock

4. One toggle switch (joy stick) for each tether (vertical and horizontal pivot)
5. Two potentiometers for position readings of each tether
6. One joy stick for simultaneous maneuvering of all three tethers in all directions. (Extension/retraction is controlled by a push button, horizontal pivoting by left and right movement, and vertical pivoting by forward and backward motion.)

Besides providing stability, the tethers, as stated earlier, will be used to aid in docking. The procedure for this is:

1. Tether positions are set to coincide with positions of tether holds at the workstation. This is done with the horizontal and vertical control motors.
2. While the Teleoperator is in free space in the vicinity of the desired workstation, the tethers are extended to a docking length of approximately four feet.
3. The clamps at the tether ends are opened.
4. The tethers are aligned with their respective holds by the attitude and control system.
5. The Teleoperator moves slowly toward the workstation until the clamps make contact with the holds.
6. The clamps are secured.
7. The tethers are simultaneously retracted to the desired working distance.

Notice that the slave arms are NOT to be used at any time during the docking procedure. It is also evident that a great amount of reliance is placed on the video and attitude and control subsystems during this time.

Because of the great amount of flexibility designed into the tethering system, it is also possible to translate from one location at the workstation to any other location within range of the system limitations. The procedure for such relocation is:

1. The Teleoperator is docked
2. The locks on the ball joints are released (the clamps continue to grip holds)
3. The Teleoperator is moved to its new location
4. The new location is reached; the ball joints are locked.

NOTE: Because the clamps do not move independently, it is necessary to perform this procedure in reverse before the Teleoperator can leave the workstation. Consequently, the clamps will always be aligned axially with the extended member. This also serves as a safety feature, in that it eliminates the possibility of the Teleoperator leaving from the new location and bumping into a hidden truss, etc.

All in all, the flexibility of this tethering system is quite unique. In fact, it is possible for the tethers to serve as backups for the manipulator slave arms due to this great amount of flexibility. While the tethers cannot ideally perform all of the manipulator tasks, the capability of performing only a few very simple tasks is a striking feature of the STEM tethers.

2.5 MASTER CONSOLE

The master console is the nerve center of the entire Teleoperator system. It is that portion where the astronaut will maneuver the Teleoperator in docking, control the slave arms, position the cameras, and monitor the engineering telemetry of the various subsystems.

The console will consist of a control panel, TV monitors, camera controls, tether controls, propulsion controls, and the master manipulator arms which will be in the form of an exoskeleton.

The exact configuration of the control panel will be determined by a systems integrator prior to launch, but the following are the requirements of the manipulator group.

a. (14) dials registering motor temperatures with red idiot lights to show over-heating.
b. (6) dials to give potentiometer readings of the tethers to enable positioning.
c. (2) dials for variable indexing potentiometers.
d. (14) toggle switches for manual braking of the motors in the manipulator arms.
e. (1) dial to monitor the position error signal in the feed back loop which triggers fail-safe braking.
f. (1) switch to reset fail-safe brakes after analysis of cause of failure.
g. (1) joy stick for simultaneous control of three tethers, including translation and extension.
h. (3) toggle switches to extend each tether separately.
i. (3) toggle switches to lock three pronged end clamps.
j. (3)toggle switches to lock ball joints on tethers.
k. (3) joy stick type toggle switches to control each tether's translation.

Presently, the console will be located in the Orbital Work Shop on the second (top) floor. It will be a one astronaut unit and will be built comfortably enough to reduce operator fatigue for a long mission time.

REFERENCES

Adamski, D. F., Seely, R. B., Unmanned Teleoperator Spacecraft (UTS) Technology, AIAA paper No. 69-1067, AIAA 6th Annual Meeting and Technical Display, Anaheim, California, October 20-24, 1969.

Brown, C. C., SKYLAB I Systems Description Document, condensed from Cluster Definition Document (ED-2002-985), Martin Marietta, Denver Division, March 1970.

Blackmer, R.H., Interian, A., Clodfelter, R.G., The Role of Space Manipulator Systems for Extravehicular Tasks, prepared for Second National Conference on Space Maintenance and Extravehicular Activities, Las Vegas, Nevada, Aug 6-8, '68.

Flatau, C.R., Compact Servo Master-Slave Manipulator with Optimized Communication Links, Brookhaven National Laboratory, Upton, New York.

Flatau, C.R., Servo Telemanipulators and Their Present and Future Applications, Brookhaven National Laboratory, Upton, New York.

Goertz, R.C., Blomgren, R.A., Grimson, J.H., Forster, G.A., Thompson, W.M., Kline, W.H., The ANL Model 3 Master-Slave Electric Manipulator--Its Design and Use in a Cave, from Ninth Conference on Hot Laboratories and Equipment, November 7-9, 1961.

Goertz, R.C., Grimson, J.H., Potts, C.W., Mingesz, D., Forster, G.A., ANL Mark E4A Electric Master-Slave Manipulator, Argonne National Laboratory, Argonne, Illinois, 1966.

Interian, A., Kugath, D., Manipulator Technology-Ready for Space Now, General Electric Co.

Interian, A., Kugath, D., Remote Manipulators in Space, General Electric Co.

Potts, C.W., Forster, G.A., Maschoff, R.H., Transistorized Servo System for Master-Slave Electric Manipulators, Argonne National Laboratory, Argonne, Illinois, November 7-9, 1961.

Scientific Experiments for the Apollo Telescope Mount, George C. Marshall Space Flight Center, Huntsville, Ala, NASA TN D-5020.

Selection of Systems to Perform Extravehicular Activities, Matrix Research Company, Alexandria, Virginia and Huntsville, Ala, April, 1970.

Study of Application of Remote Manipulation to Satellite Maintenance, Final Report, Vol. II: Technical Report, Contract No. NAS 2-5072, NASA Report No. R-73-339, General Electric Co.

PERSONAL CONFERENCE REFERENCES

Bernier, Richard, Residual Sales Manager, Inland Motor Corporation of Virginia, Radford, Virginia.

Flatau, Mr. Carl, Brookhaven National Laboratory, Upton, New York.

Jones, John D., Laboratory Supervisor, Phoenix Memorial Laboratory, University of Michigan, Ann Arbor, Michigan.

Kugath, Donald, General Electric Company

McMahon, Prof. Department of Electrical Engineering, University of Michigan, Ann Arbor, Michigan.

Mingesz, Donald P., Argonne Laboratory, EBR-II Project, Argonne, Ill.

USM Corporation, Gear Systems Division, Wakefield, Massachusetts.

Walker, J. F., Stem Marketing, Spar Aerospace Products Ltd., Toronto, Canada.

Warren, H. R., Chief Systems Engineer, Spar Aerospace Products Ltd., Toronto, Canada.

Weir, F. H., USM Corporation, Birmingham, Michigan

Williams, Prof. W. J., Department of Electrical Engineering, University of Michigan, Ann Arbor, Michigan

3
VIDEO

3.1 INTRODUCTION

The video system of the Teleoperator must be designed to enable the operator to dock the Teleoperator with its target and to allow the operator to adequately perform Teleoperator worksite operations. The components of the video subsystem are:

- cameras
- lenses
- zoom, focus, and aperture controls
- control units
- pan and tilt controls
- illumination devices
- housekeeping sensors
- monitors and controls inside Skylab

The subsystem must be able to operate in a space environment for one year. It must also withstand a Saturn V launch. We will use "off the shelf" hardware whenever possible.

3.2 THE CAMERA SYSTEM

3.2.1 Camera Configuration

Three monochromatic cameras will perform the viewing functions. However, only two of them will be operating at one time. One camera (camera I) is mounted on a semi-rigid tether. The others are mounted on a platform situated approximately "head-height" above, and between the shoulder joints of the manipulators. This will provide a normal viewing reference for the operator.

One of the platform cameras (camera II) will be permanently mounted; the other (camera III) will be mounted in a bracket and will be attached to a semi-rigid tether. This bracket-mounted camera is removable from the platform, but will be detached only if it, or the tether-mounted camera (camera I) should fail.

Cameras II and III, mounted on the platform, will be operated in a synchronous mode for docking purposes. The platform will aim them in exactly parallel directions, tilt them $\pm 90^{\circ}$, and pan them 360°. A mechanical linkage will focus, zoom, and control the aperture openings on cameras II and III, together. All this will provide stereo vision for docking purposes (to be explained later). Since it provides the operator with enhanced video depth perception, stereo vision will enable him to dock the Teleoperator more easily and safely.

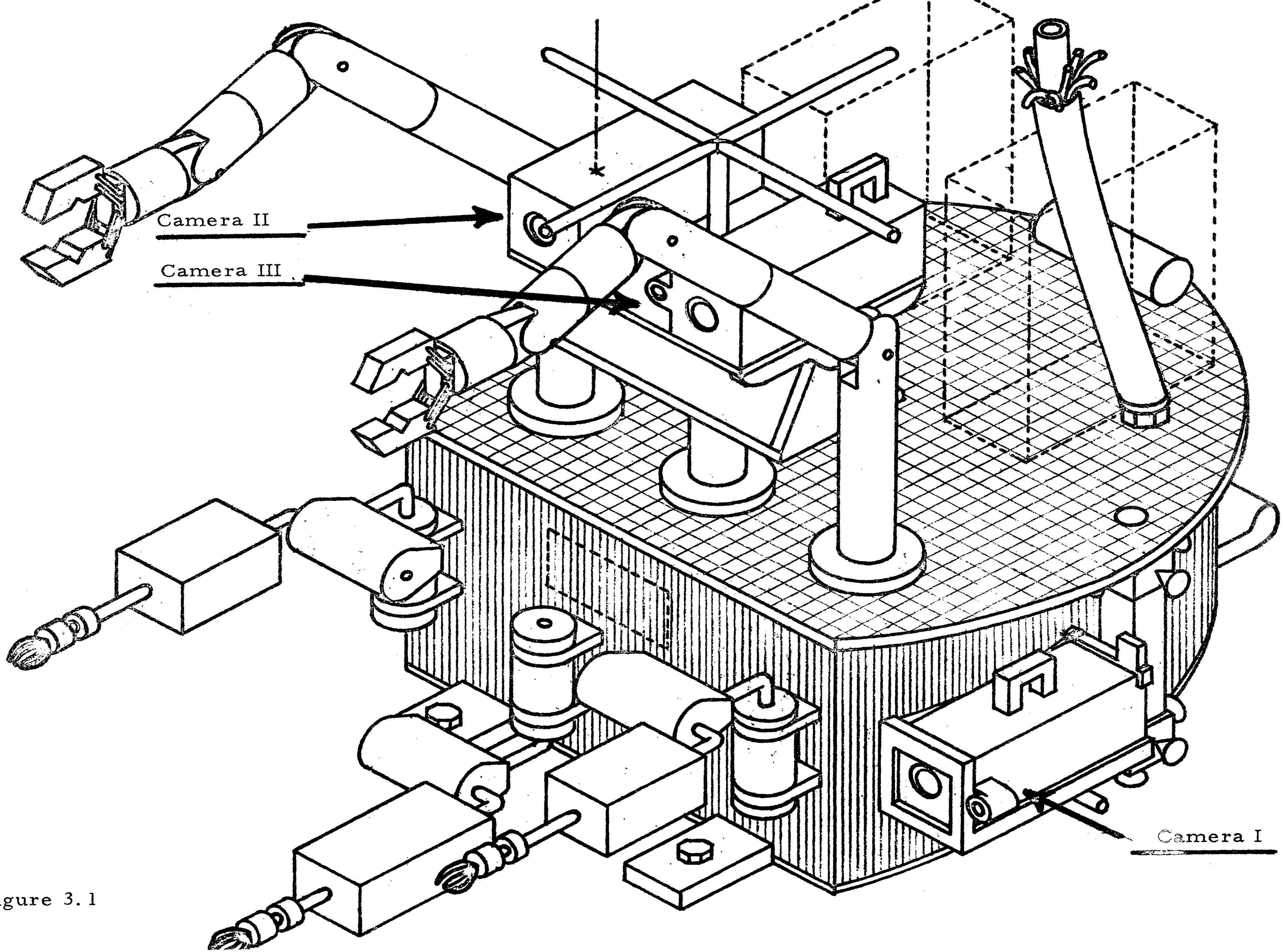


Figure 3.1

Once docking has been achieved, camera III will be turned off, camera I will be turned on, and work operations can begin. Camera I is tether-mounted on the left hand side of the Teleoperator body so as to provide as much freedom of movement as possible for the right manipulator arm, which will be performing most of the worksite operations.

Camera II will remain on whenever the Teleoperator is in use. During worksite operations the mounting platform will pan and tilt cameras II and III so that camera II can view the worksite. The combined viewing of cameras I and II from different angles, will enable the operator to accurately judge distances and perform the worksite operations. The platform tilts downward so camera II can view the tool box for tool access. It should be noted that cameras II and III are still operating synchronously via the mechanical linkage. This will maintain the stereo viewing capacity for later use.

3.2.2 Camera Back-Up Systems

If camera I should be damaged or fail, the mechanical linkage between cameras II and III will be disengaged, camera III will be switched on, removed from its bracket, and will function in camera I's place. Cameras II and III will now be zoomed, focused, and have their apertures controlled individually. Also, camera II will have been switched into an individual pan mode to enable the operator to point camera II directly at camera III while the manipulator reaches up and removes camera III from its bracket. When all this has been accomplished, work operations can continue. Also, with camera III mounted in its bracket and the mechanical linkage engaged, the Teleoperator will still have stereo vision capacity for docking.

If camera III should fail, work operations can still continue using cameras I and II. Camera I and III will be completely interchangeable; a bracket mount on camera I allows it to fit in camera III's platform bracket. Stereo vision is still available for docking if cameras I and III are interchanged, and the mechanical linkage is engaged between cameras I and II.

If camera II should fail, the Teleoperator will have lost its stereo vision capacity. Docking operations will now be more difficult to perform as the operator will have impaired depth perception. Work operations, however, can continue using cameras I and III.

3.2.3 Camera Tube Description

The camera we will use is the General Electric UVR-700 FPS (Focus Projection Scanning) Vidicon Camera. This is a small, lightweight device and requires a small amount of power (see Appendix B, Part 2).

It utilizes a silicon target, thus making the camera tube safe from burnout due to direct exposure to the sun. At a 4 MHz signal bandwidth, this camera tube can provide resolution of 0.1 inches at a distance of two feet from the target. At this bandwidth, the camera tubes will provide 525 lines/frame at 30 frames/sec. This will allow the Teleoperator to perform all of the planned worksite operations. The UVR-700 FPS also produces excellent edge resolution, and has a good signal current output. This camera tube is not flight tested, but silicon vidicon camera tubes will be flown on Apollo 14, so they will be tested long before a Teleoperator flies on Skylab.

3.2.4 Control Units

There will be three control units, although only two will be operating at one time. Coaxial cable provides a hardline link between the tubes and the control units. Each control unit contains a sync generator, sweep generator, video processor and an automatic gain control for the target voltage of the camera tubes. Weight, size, and power requirements are presented in Appendix B, part 2.

As the control units are mounted inside the Teleoperator body, they are protected from impact damage. This is the primary danger. Environmental damage is of minor concern as thermal conditions can be controlled. In the event that a control unit should fail, there is a spare. Each camera tube can be switched from one control unit to either of the others, so no matter which control unit fails, the Teleoperator will have full video capability.

The cable bundle must carry leads for power, and for a power ground, both insulated, to the camera casing. It must also carry two coaxial leads, the video signal on the central conductor, and a signal ground on the outer braid. The cable bundle must also carry temperature sensor data. A double wrap Teflon jacket will cover the coaxial cable, and an outer sheath of braided glass covers the entire cabling bundle.

The flexible cables for cameras I and III will carry this cabling bundle inside a semi-rigid sheath. We estimate the length of the tethers to be 6 feet, but laboratory studies should be made to determine the optimum length.

3.2.5 Lenses

Each of the three camera tubes will be equipped with a zoom lens. This will provide more than adequate viewing for docking and work purposes. It is necessary to have zoom lenses on all three cameras to provide for interchangeability.

We will be using Angenieux Corporation of America's 10 x 12 A2 zoom lens. Its specifications are noted in Appendix B, part 2. This is a very good lens, with a zoom factor of 10, and an ability to focus on objects as close as 2.5 feet away. Herein lies a weakness; if camera III is needed to replace camera I, camera II will have to view camera III, and the distance between these cameras is only 14 inches. Therefore, an additional lens will need to be placed in front of the zoom lens to allow camera II to focus on camera III should this backup operation become necessary.

The maximum object angular field is 67^{o} with the lens zoomed all the way out - the condition for docking. This will provide very good overlapping of the two platform camera images during docking operations, thus producing a good stereo image.

3.2.6 Camera Enclosures

The camera housing consists of a machined, combined structural and thermal, radiating plane. The optics interface is through the forward face of the enclosure. Moisture and dust sealing is provided at all interfaces. The housing material is aluminum, chosen for its strength, lightness, ability to be machined, relatively good anticorrosion nature, and thermal conductivity.

Protection against outgassing and subsequent recondensation of materials is essential to avoid contamination of the optical surfaces and consequent image degradation. Materials on the surface of the camera tube are potential sources of vapor, and should be vacuum devaporized at temperatures in excess of mission conditions prior to launch.

All non-conductive moving parts within the housing should be coated with 10 to 20 x 10^{-6} inches of Ball Brothers Res. Corp. solid space lubricant, molybdinum disulfide. This is an excellent lubricant and it will not degrade during the Teleoperator's one year mission life.

3.3 PRINCIPLES OF STEREO OPTICS

3.3.1 General

The video subsystem will provide stereo television to give the operator some measure of depth perception to aid him in the docking maneuvers. Real stereo vision will not be provided, but the illusion of it will be induced in the operator's mind. This is to be accomplished by mounting cameras II and III parallel to each other on the head. These cameras will be mechanically linked to provide synchronous zoom and focus, and synchronous control of the aperture openings. The video information gained by this system will be sent to Skylab, where it will be displayed on two monitors and then optically combined and displayed on a single screen in front of the operator.

3.3.2 Basis of Stereo Vision

The cues for depth perception fall into two classes, monocular and binocular, as follows:

a. Monocular
   1. Relative size of objects
      (larger object appears nearer)
   2. Light and shade
      (highlighted object appears nearer)
   3. Overlap
      (overlapping object appears nearer)
   4. Perspective
   5. Visual contrasts
   6. Movement parallax
      (nearer objects move against distant objects)
   7. Object detail
      (distant objects are indistinct)

b. Binocular
   1. Convergence
      (the angle of convergence of the lines of fixation gives a cue of depth)
   2. Stereoscopic vision
      (the difference in convergence angles formed by the lines of sight to the objects viewed)

All of the monocular cues can be obtained from either camera on the head. For the binocular cues, the convergence factor will be ignored because a system to keep the lines of fixation of the camera automatically convergent would be extremely complicated. Also, performing this task would necessitate adding another series of steps to an already complicated operating procedure.

Therefore, we must use the stereoscopic cue if we wish to enhance the depth perception already obtained from the monocular cues. The stereoscopic effect is caused by retinal disparity. This disparity is proportional to the difference in depth of the two points in the field being viewed, and inversely proportional to the average object distance squared. This is primarily a geometrical consideration. If instead of viewing the scene directly, we can view it using our television monitors, and produce a similar geometry, the resulting image will produce a retinal disparity and hence stereoscopic vision.

To achieve this effect we will mount two cameras in the head with their lines of fixation parallel. The baseline separation between the cameras is an important variable, and we have chosen our baseline to be 14 inches.

This maximizes the stereo effect at the closer ranges where it is the most critical. The baseline separation ideally would be slightly larger, but due to the location of the manipulator shoulders a maximum size of 20 inches was imposed on the head assembly.

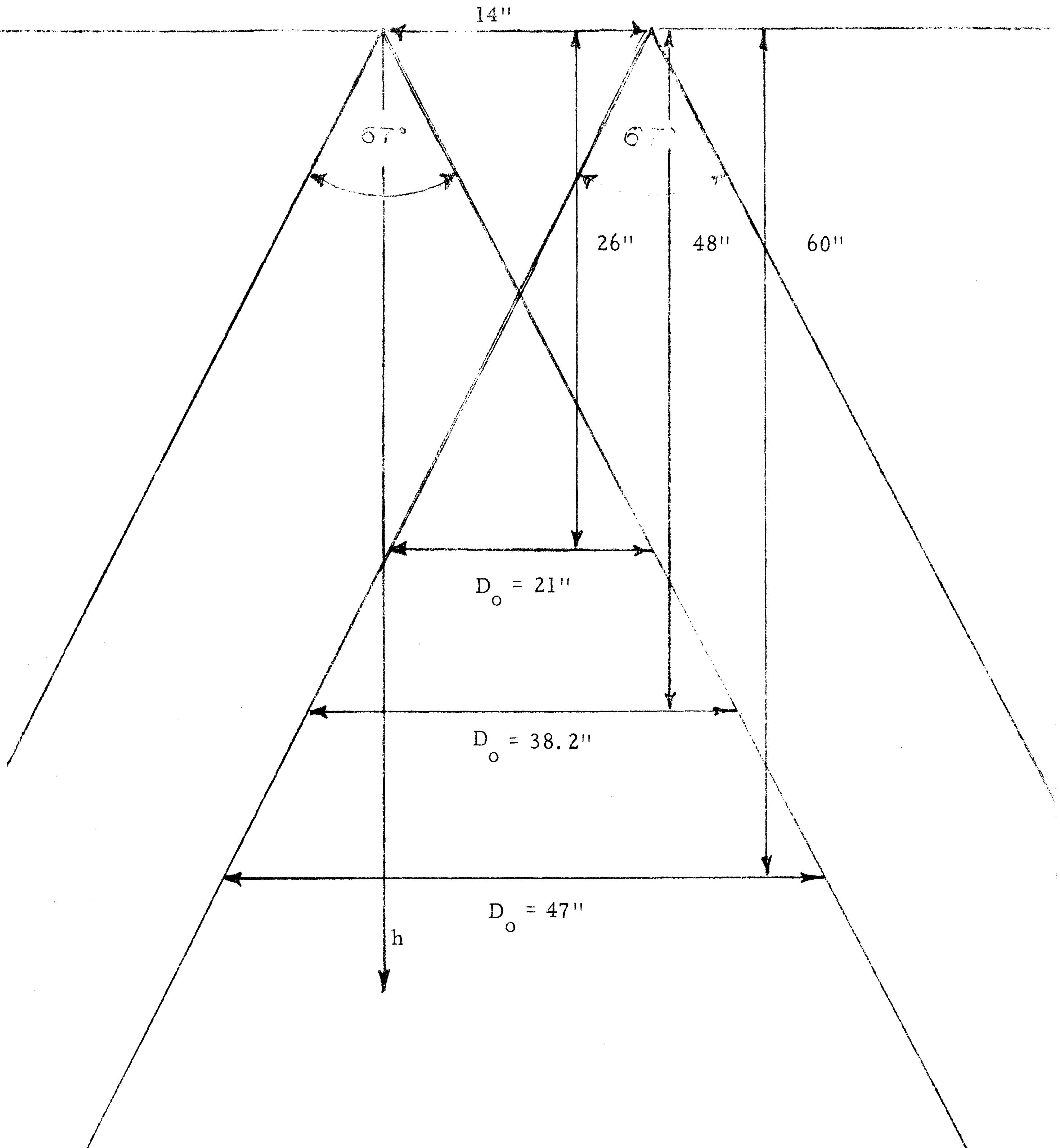
The stereo effect is only present under two conditions. First, the overlap of the two images must be large, for it is only in this area that the two angles of view are present. Second, the difference in depth of two points being viewed must be of the order of magnitude of the average object distance. Our system will provide good stereo viewing from approximately 2.5 feet to approximately 5.0 feet. Inside the 2.5 foot range, the overlap area approaches zero, and beyond the 5.0 foot range the difference in depth is becoming small compared to the object distance. Figure 3.2 shows the relationship between stereo viewing area and distance from target.

3.3.3 Presentation of Stereo Effect

Many methods of presenting a stereo view are possible, all of which operate on the same basic principle: the two different views are each presented to the respective eyes and the viewer's mind assimilates the information presented. We considered three systems:

1. The operator wears a mask, to which the video information is transmitted. A hood then displays this information in front of the appropriate eye.
2. The output of each camera is displayed on monitors behind the control panel. A filter of different color, perhaps red and blue, or red and green, will be placed in front of each monitor, and the outputs optically combined to be displayed on a translucent screen on the control panel. The operator would then wear a pair of glasses with different colored lenses, the color of which would correspond to that of the appropriate monitor. In this way each eye would receive only the appropriate view.
3. The output of each camera is displayed on two monitors behind the control panel. A polarized filter is placed in front of each monitor, one oriented 90° from the other. The outputs would then be optically combined and displayed on a single translucent screen on the control panel. The operator would then wear glasses which would be polarized as the monitors are. In this way the inappropriate view would be filtered out.

System 1 is the least desirable of the three in that it would be bulky, probably fatiguing, and would make it difficult for the operator to monitor the other control data. System 2 is much better in that it would not be so bulky, and the operator could still view the rest of the control panel. However, the two-colored view of the rest of the control panel might cause eye fatigue and lead to a misinterpretation of lights on the panel.



D_o = Diameter of Overlap
$D_o = 1.2 \times h \times \tan\frac{\theta}{2}$ for a 14" camera separation

Figure 3.2 Diameter of Overlap as a function if Distance From the Target

System 3 is the best because, to the operator, everything on the control panel appears normal, as if he were viewing it without the glasses. This would probably be the least fatiguing, and it would reduce the chances of misinterpretation. However, this system does have some problems. The first is that the monitor outputs must have their intensities increased, perhaps doubled, because the 50-50 beam splitter allows only 50% of the light from each to reach the screen (see Figure 3.2). This problem can be corrected by stepping up the tube voltages on the monitors. Another problem is that care must be taken so that the polarized light from each monitor is not depolarized before reaching the operator's glasses. If it is, the stereo effect will not be achieved. For this reason care must be taken in the choice of the translucent screen material.

Finally, stereo vision is not really essential for depth perception; the monocular depth perception cues are sufficient. However, the stereo provides an additional helpful cue, and for such critical operations as maneuvering and docking, we feel that stereo is worth the extra effort because of the extra security it provides.

3.4 ILLUMINATION

3.4.1 Lighting in Bright Sunlight

Under conditions of high intensity illumination, the beam current of the camera tube tends to rise, and it is possible that the image will be washed out entirely. To prevent this, an automatic light control (ALC) will be mounted on each camera tube. This device operates over an illumination range of one foot candle to 8000 foot candles scene illumination. It is a servo-controlled, variable density, neutral filter system. Inconel, the flattest of neutral density filter materials, will be used. Also an ultraviolet rejection filter will be applied to avoid possible fluorescence of the high index glass lenses, with a resultant loss in image contrast. There will also be an automatic aperture control on each camera tube.

The purpose of the ALC is to free to operator from worrying about the picture washing out, as the ALC will filter out any dangerously excessive illumination. Since the ALC operates on average incoming illumination and does not perceive areas of intense light, there still may be areas of high intensity illumination. There must be a manual aperture control for each camera which can override the automatic aperture control whenever there are areas of high intensity illumination.

3.4.2 Lighting in Shadow

The General Electric UVR-700 FPS Vidicon Camera has the ability to see with as little as 0.01 foot candles scence illumination. To do this, however, the lines/frame must be cut from 525 lines/frame to approximately

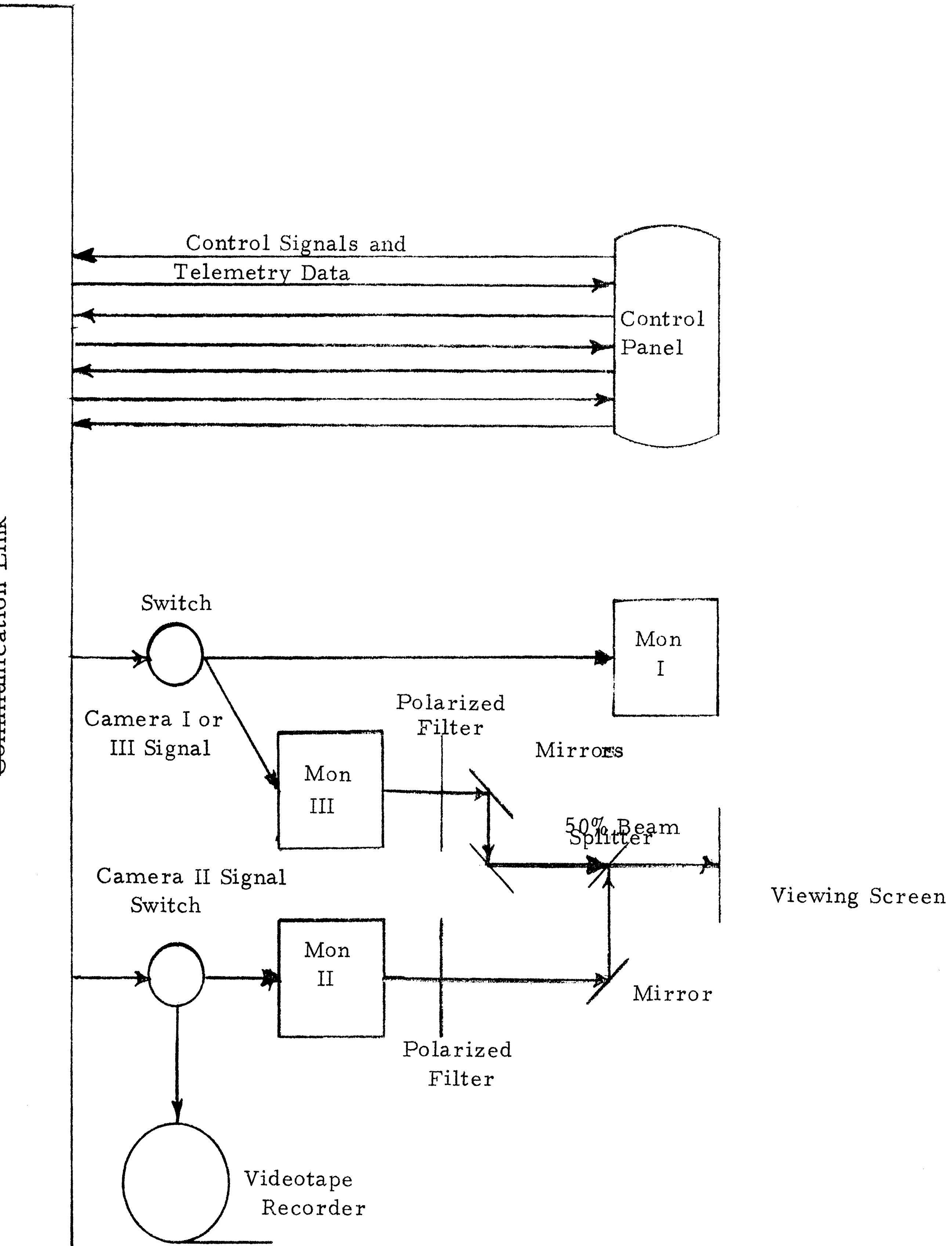


Figure 3.3 Skylab

200 lines/frame, with an associated drop in image size and resolution. Two one-watt bulbs can provide 0.01 foot candles, but we will provide 5 watts illumination/camera, a total of 15 watts. This will allow the camera to operate at, or near, the normal 525 lines/frame. The illumination devices will be high pressure Xenon lamps. These illumination sources are highly efficient; they provide more useful light flux than incandescent bulbs, and they consume less power as well as generate less heat than the incandescent bulbs. Also, Xenon lamps provide illumination which can be directed or focused easily. The lamps will be mounted in a protective sheathing on the camera enclosures.

3.4.3 Lighting Under Light/Dark Situations

Under conditions of light/dark contrast, two problems arise. The high intensity light can force the beam current to rise, with the possibility of washing out the image. Also, the light/dark contrast produces an image which makes control of the Teleoperator difficult for the operator. He cannot "see" well - resolution is poor, and depth perception is impossible to effect.

We had considered using diffuser-reflectors to spread the intense light over the dark areas, with Automatic Light Control used to prevent image washout. This would be ideal, as we would be using existing power (sunlight) rather than drawing on the Teleoperator's batteries. The drawback is that diffuser-reflectors must be tether-mounted, and these additional tethers would clutter the worksite.

General Electric is presently developing two techniques - Automatic Beam Control, and the Anti-Comet-Tail Gun - which we plan to use for this operating condition. The Automatic Beam Control limits the beam current to keep highlights (areas of high intensity) from blooming and washing out the image. The Anti-Comet-Tail Gun is a device that discharges the highlights from the image during retrace. These two devices will effectively eliminate the light/dark contrast from the monitor picture. Both of these techniques must be miniaturized, packaged, and flight qualified before they can be flown. They are video state-of-the-art, however, and we will use them.

3.5 CONTROL PANEL

The control panel will be located in a convenient place onboard Skylab, either in the OWS or the MDA. There will be two monitors behind the panel, with their images optically combined and displayed on a translucent screen on the control panel. During worksite operations when the stereo is shut down, camera III will be turned off, and only the view from camera II will be shown on this screen. A third monitor will be mounted next to this screen to give the view from camera I when it is in operation. This monitor and the translucent screen should be mounted at eye level in front of the operator to reduce the likelihood of fatigue.

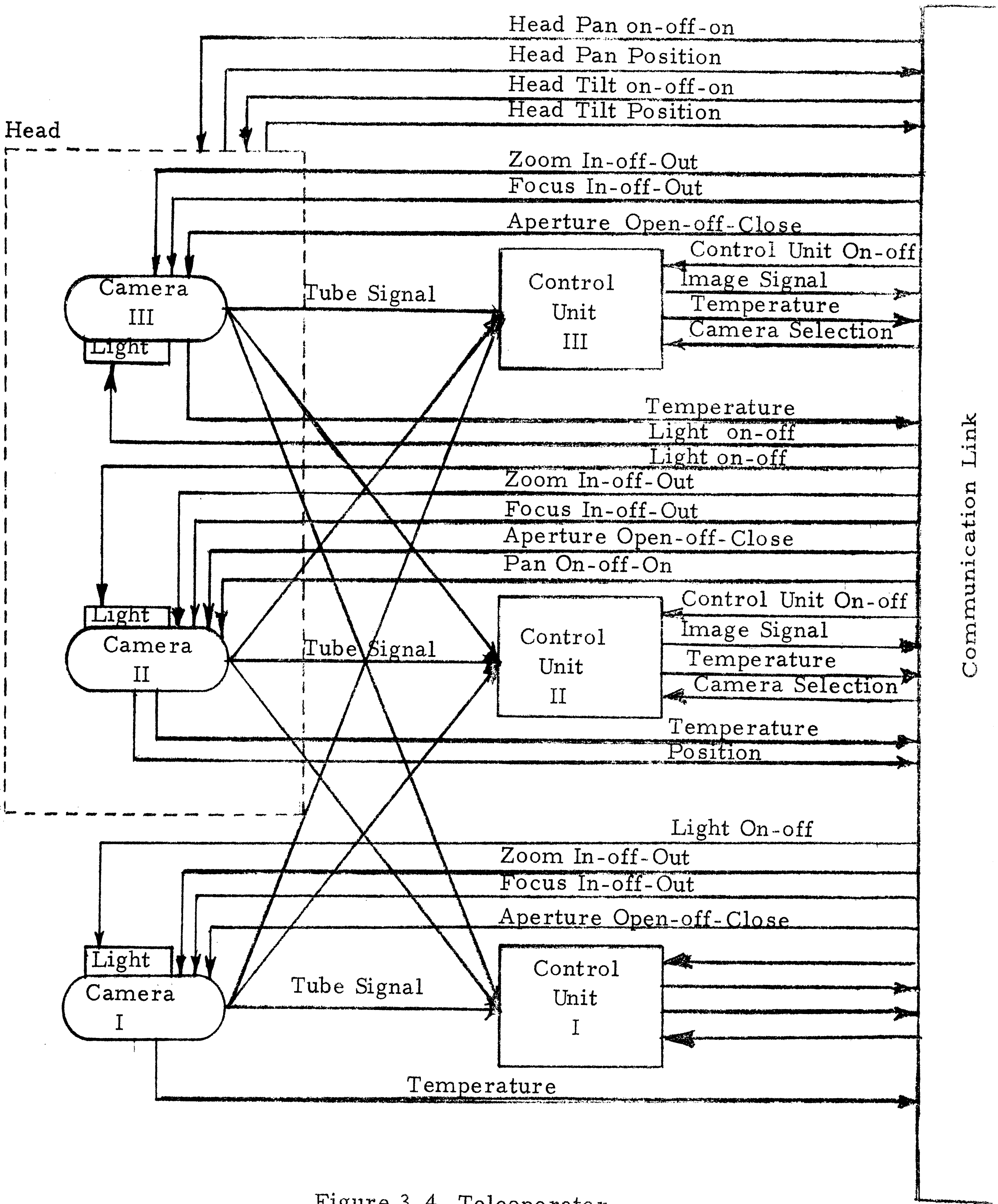


Figure 3.4 Teleoperator

The controls for the operation of the cameras (see Figure 3.4) will be located in groups, one group for each camera, with a fourth group controlling the motion of the head, and a fifth to provide for interchanging the cameras and control units in case of failure. The camera control switches will be three position toggles (e.g. IN-OFF-OUT, in the case of the zoom). The head controls would be of the same type for pan and tilt. Also in the head control group, a readout of camera pan position and tilt position will be included. This is necessary because after a long series of different camera motions, the operator may become disoriented. He needs to know his cameras' positions relative to a reference position before he attempts to move the Teleoperator. The camera control unit group will provide three switches, one for each control unit. Each switch will enable the operator to switch camera tubes and control units in case of failure of either.

Also included in the control panel will be gauges and "Idiot" lights to display the camera tube and control unit temperatures.

The control panel will also give the operator the ability to video-tape scenes he feels may be interesting or useful later on. These tapes could perhaps be returned to earth in the Command Module or possibly transmitted down via Skylab's communication link.

Sources of Information

1. American Society of Photogrammetry, Manual of Photogrammetry, Volumes I and II, Morris M. Thompson, Editor-in-Chief, George Banta Co., Menasha, Wisconsin, Copyright 1966.

2. NASA-CR-98279, "Ultraminiature Television Camera" Final Report June 1967-Feb. 1968, R.J. Sussman (Teledyne Systems Co.)

3. NASA-CR-61630, "Stereo TV Enhancement Study", Final Technical Report, E. Hudson, et al (Kollsman Instrument Corp.)

4. NASA-CR-65987, "Lunar TV Camera", Final Report, Westinghouse Electric Corp., June 1, 1967.

5. Elements of Television Systems, Anner, George E., New York, Prentice-Hall, 1951.

6. "The Apollo Color Television Camera", Westinghouse Engineer, November 1968.

7. Information forwarded by:
    1. McDonnell Douglas Astronautics Company
    2. Ball Bros. Research Corp. (Aerospace Division and Standards Lab.)
    3. General Electric Company
        a. Space Systems - Philadelphia, Pa.
        b. Aerospace Electronic Systems - Utica, N.Y.

4. Angenieux Corporation of America
5. Zoomar, Inc.
6. Wollensak TV Products
7. Canon U. S. A., Inc.
8. Westinghouse Electric Corporation

4
ATTITUDE CONTROL AND PROPULSION

4.1 SYSTEM

The nature of REMUS's mission requires that the spacecraft have an accurate attitude control system. It must be capable of docking, undocking, and flying near sensitive equipment without causing damage due to its thruster exhaust. In addition, the attitude reference system must be independent of line-of-sight requirements since Skylab may block this line of sight during a given mission. These criteria form the basis for the selection of an attitude control system for REMUS.

4.1.1 Attitude Reference

REMUS will employ an attitude reference subsystem consisting of a rate gyro package and a rate integrating gyro package in a strapdown configuration. The outputs of the rate gyros give the angular rates the spacecraft is experiencing, whereas the rate integrating gyros provide the attitude angles directly. This method of attitude reference provides simple attitude rate and attitude information without the necessity of calculations.

The mission requirements of REMUS dictated the use of this method of attitude sensing. Star trackers, horizon sensors, and sun sensors are ruled out because of the probable obstruction of one or more of these references by Skylab. Through use of rate gyros and rate integrating gyros REMUS becomes independent of any outside reference after the initial startup phase. Small drift rates and a ten hour mission life enable this system to function with acceptable accuracy during the entire mission life. Drift rate for the rate gyro is $\pm$ 0.005 deg/hr and the drift rate for the rate integrating gyro is $\pm$ .01 deg/hr.

4.1.2 Actuators

Reaction Wheels

Reaction wheels are momentum storage devices that can, through a change in flywheel speed to effect a momentum change, impart moments to the spacecraft body to counter external distrubance torques. These momentum wheels can therefore act as continuous and automatic stabilizing elements. Commands to the reaction wheel are in the form of error signals, as will be shown later.

If disturbance torques are in the same direction for an extended length of time, the reaction wheels may become saturated, that is, the motor speed is such that no further torque can be imparted to the wheels. This generally occurs slightly below synchronous speed. If saturation should occur, the wheels

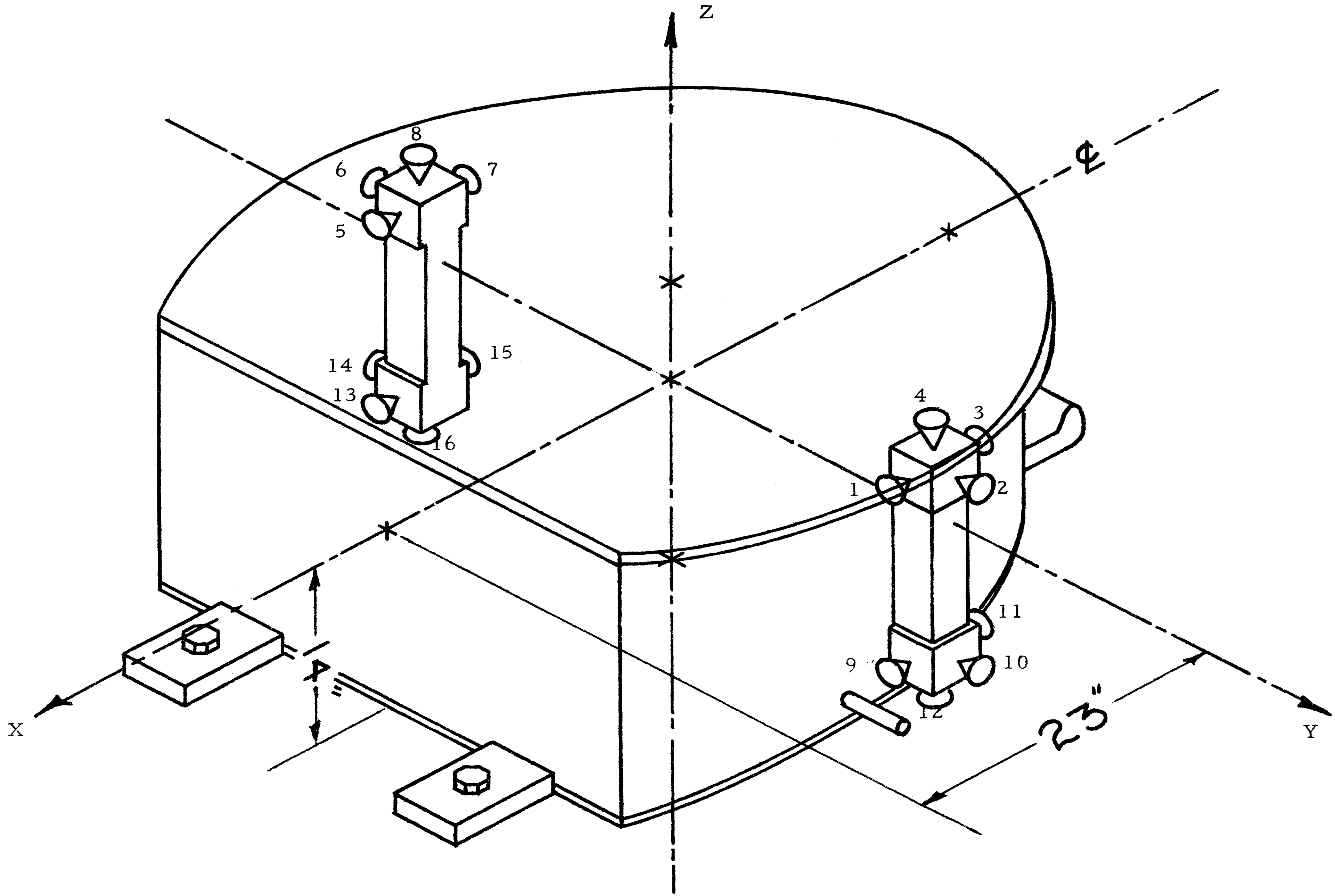


Figure 4.1 Body Axes and Thruster Positions

may be desaturated by firing appropriate thrusters in a direction opposite to that of the disturbing torques. This desaturation is performed automatically on command from the tachometer which is contained within the reaction wheel assembly.

Cold Gas Thrusters

With REMUS flying near sensitive scientific equipment it is desirable that no hot gas impingement from thrusters occur. The alternative to a monopropellant system in this case is a cold gas thruster system. This system consists of a tank with inert gas under pressure (in this case N_2), a valve system, and the thruster itself. The thrust provided is small (0.5 lbf/thruster), but this is sufficient for REMUS since the expected range is quite small and the desired relative velocity does not exceed 0.5 fps.

The thrusters will be mounted in four clusters of four thrusters apiece. They are placed in such a position that they may be used for translation or rotation.

4.1.3 Control System Design

Stabilization

We shall define stabilization as maintaining a desired attitude, e.g. $\phi = 0$, $\theta = 0$, $\psi = 0$.

Shown in Figure 4.2 is the automatic stabilization control system. In the feedback loop of the system, the rate and rate integrating gyros sense any deviations from the null position. The gimbal pickoffs of the gyros send a voltage signal to the summer to produce an error signal. The error signal is then amplified in the servoamplifier; the resulting signal is then integrated and resummed producing an error signal to the motors of the reaction wheels. The motors will put a larger or smaller, torque to the wheels, which will increase (or decrease) the wheels angular momentum to compensate the disturbance torque REMUS is experiencing, and bring REMUS back to the desired attitude. The wheel speed is monitored by the tachometer. If the wheel speed is above a predetermined level, thrusters are fired to desaturate the wheels.

Figure 4.2 suggests a decoupling of motion. Although the equations of motion of REMUS are very coupled (see Appendix C) this model will suffice for a preliminary design. If actual results show this model leads to large attitude errors, compensation will have to be included in the loop. A discussion and proposed analog simulation of this model is presented in Appendix C.3.

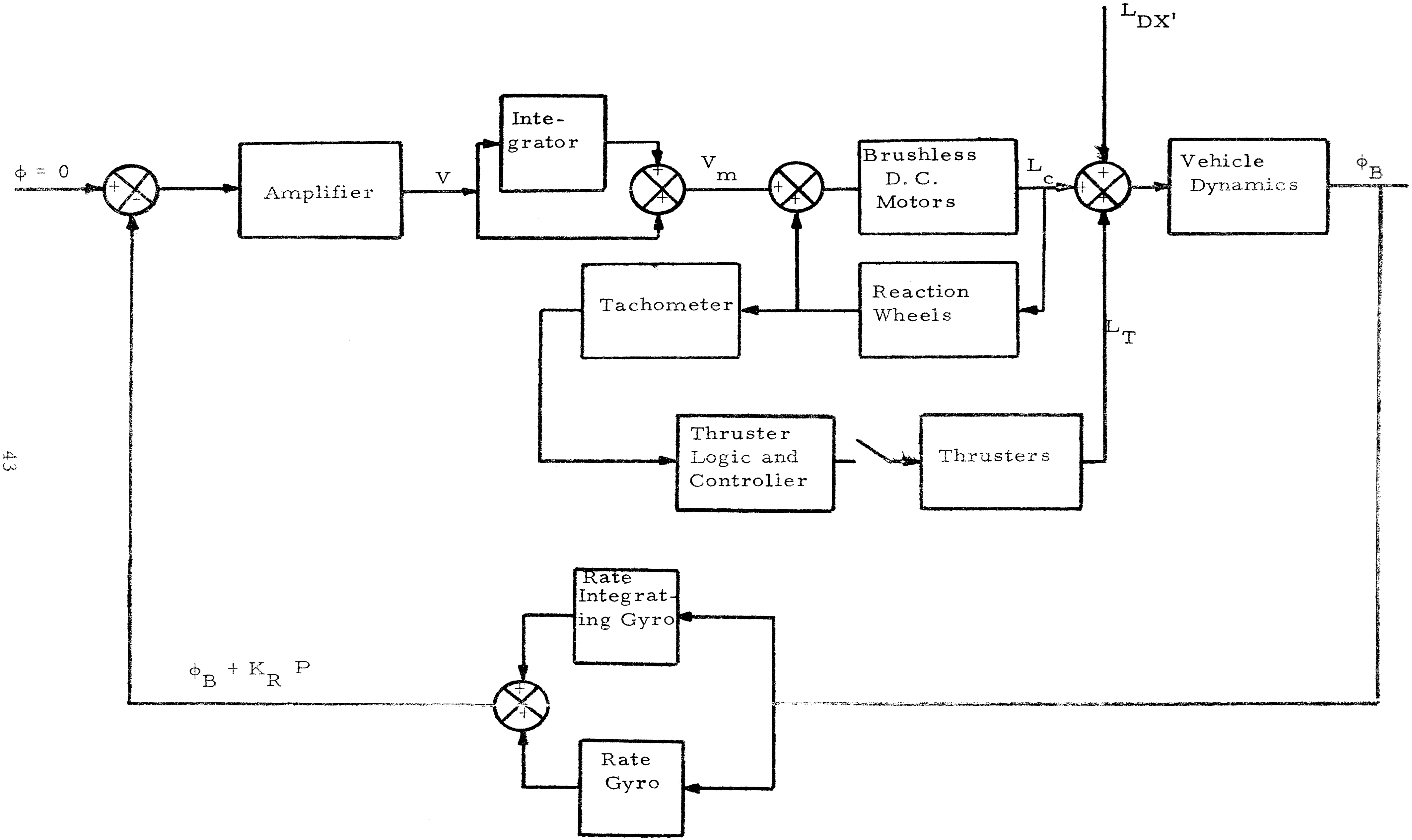


Figure 4.2 Roll Stabilization Channel

The control system of Figure 4.3 is easily recognized as proportional plus derivative plus integral control. From the standpoint of stability, rate information, as given by the rate gyro, is very desirable. A high gain constant (proportional control) K_A will effectively reduce the threshold effects of the gyros. And the addition of integral control will result in no steady state errors. This control system enables REMUS to stabilize automatically at a desired attitude without any influence from outside the spacecraft.

Commanded Attitude Change

There will be two modes of operation for attitude changes. From Appendix C.1 the rate integrating gyro has a maximum input angular displacement of $\pm$ 10 degrees. If this limit is exceeded, the gimbal encounters the stops and no further output axis displacement can occur, even though the input displacement may exceed 10 degrees. What this means is that a commanded attitude change of less than 10 degrees can be handled by the rate integrating gyro, thus maintaining the inertial reference on board. For attitude changes of more than 10 degrees, the rate integrating gyro must be caged (locked by the gyrotorquer in its null position) to prevent erroneous error signals to the thrusters. With the loss of this inertial reference, attitude change commands must be inputted as desired rate commands. The two modes of operation can now be recognized as:

A. High Pointing Accuracy for Small Attitude Changes.

Figure 4.3 depicts this mode. Note that the commanded input is still 0. The desired attitude change is introduced into the control loop as an error signal by the gyro torquer. The basic principle is that by carefully controlling the current, the gyro torquer can displace the output axis of the rate integrating gyro exactly the negative of the desired attitude change. The gimbal pickoff senses the "error" and the thrusters are activated to compensate for the "error." Slightly before the null position of the gyro is reached the reverse thrusters are fired to stop the angular rate. The stabilization mode is then activated to stabilize about the new attitude. The rate gyros are caged during the attitude change by its gyrotorquer, again to prevent undesired error signals.

This high accuracy mode will be most useful for docking attempts, where accuracy is demanded for alignment of the docking tethers. The underlying assumption is, of course, that REMUS can be brought to within ten degrees of the desired attitude; this will be the function of the second rotational mode.

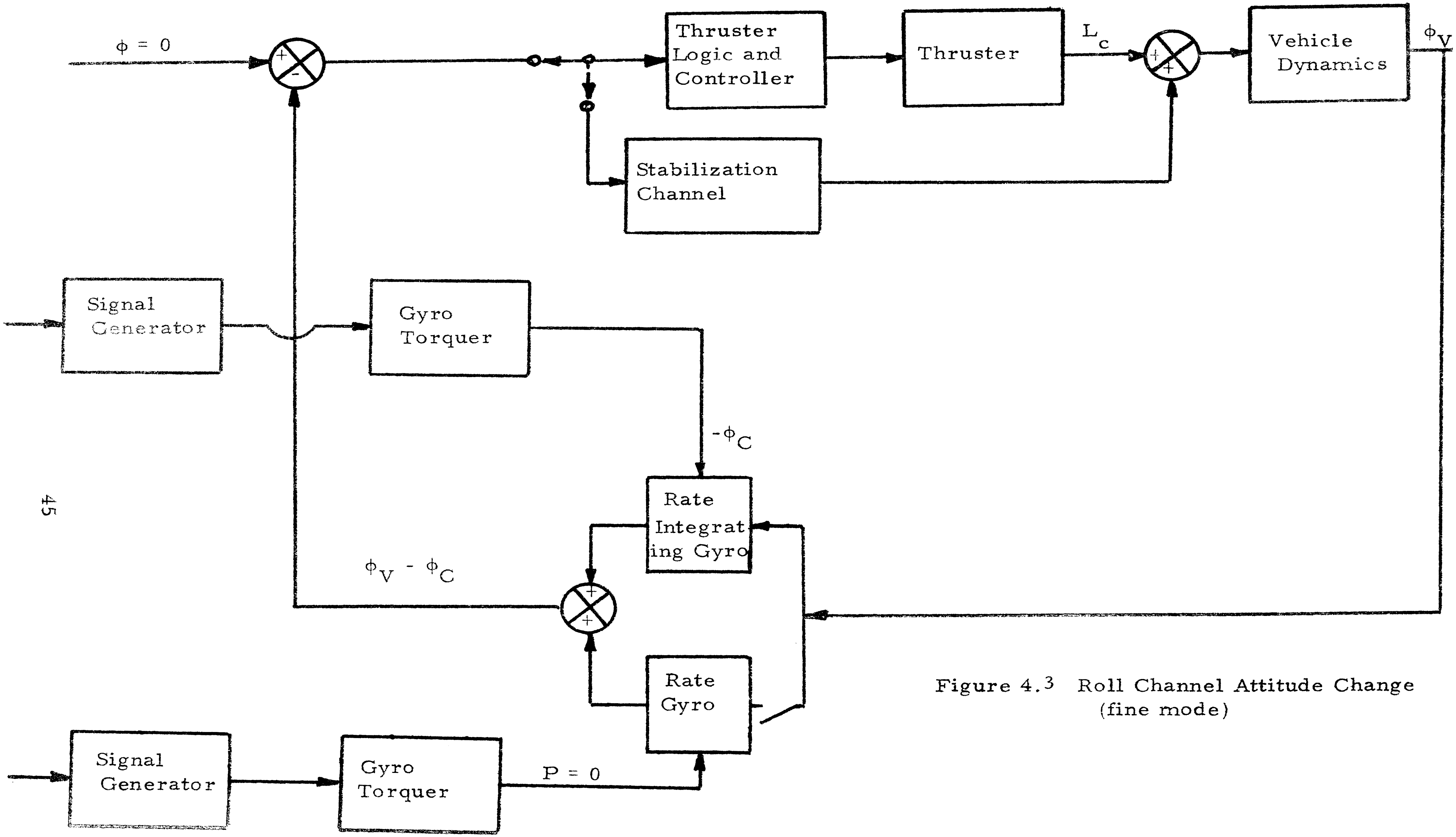


Figure 4.3 Roll Channel Attitude Change (fine mode)

B. Low accuracy rate commands for the inspection trip and initial alignment for docking REMUS will be required to make attitude changes greater than the ten degree limit. In this mode the rate integrating gyro will be caged leaving only the rate gyro in the feedback loop. Figure 4.4 is the control loop for this mode. The astronaut, based on his visual observations, inputs a rate command. In response to the command, the thrusters are pulsed until the desired rate is produced, as sensed by the rate gyro. When the astronaut wants to stop the rotation at a desired attitude, he will have to estimate the time at which to "reverse" thrust. To expect high accuracy attitude control from this mode is, at best, naive. However, as noted earlier, the astronaut need only come within ten degrees of his desired attitude. After this is attained, he may specify his attitude chang in degrees, rather than a rate.

Both modes employ man in the control loop. Implicitly assumed in both modes is that the astronaut spend many hours in simulation to minimize this "trial and error" procedure.

4.1.4 Computing Requirements

Computing will be needed on Skylab, either through use of Skylab's own computer or an additional computer to be placed on board Skylab.

Under normal operating conditions the computer will compute signals to be sent to the signal generators of the rate integrating gyros in response to an attitude change command. It will also compute thruster commands for an abort vector when REMUS is approaching Skylab in case of communications loss. This will be discussed in detail later.

Also to be discussed later is the possible requirement of differentiating and/or integrating in different failure modes of operation.

Pilot Commands

The REMUS pilot may override any phase of the system operation when necessary. Normally he only needs to command attitude changes and translational changes.

4.2 FLIGHT PROCEDURES

4.2.1 Startup

Prior to the deployment of REMUS, a startup of the subsystems must take place. Initially this means turning on the gyro heaters, which heat the gyro fluid to its operating temperature. The fluid in the rate integrating gyro must be kept in a small temperature range about $180^{\circ}F$ for the gyro to operate properly, since the fluid viscosity varies rather drastically with temperature.

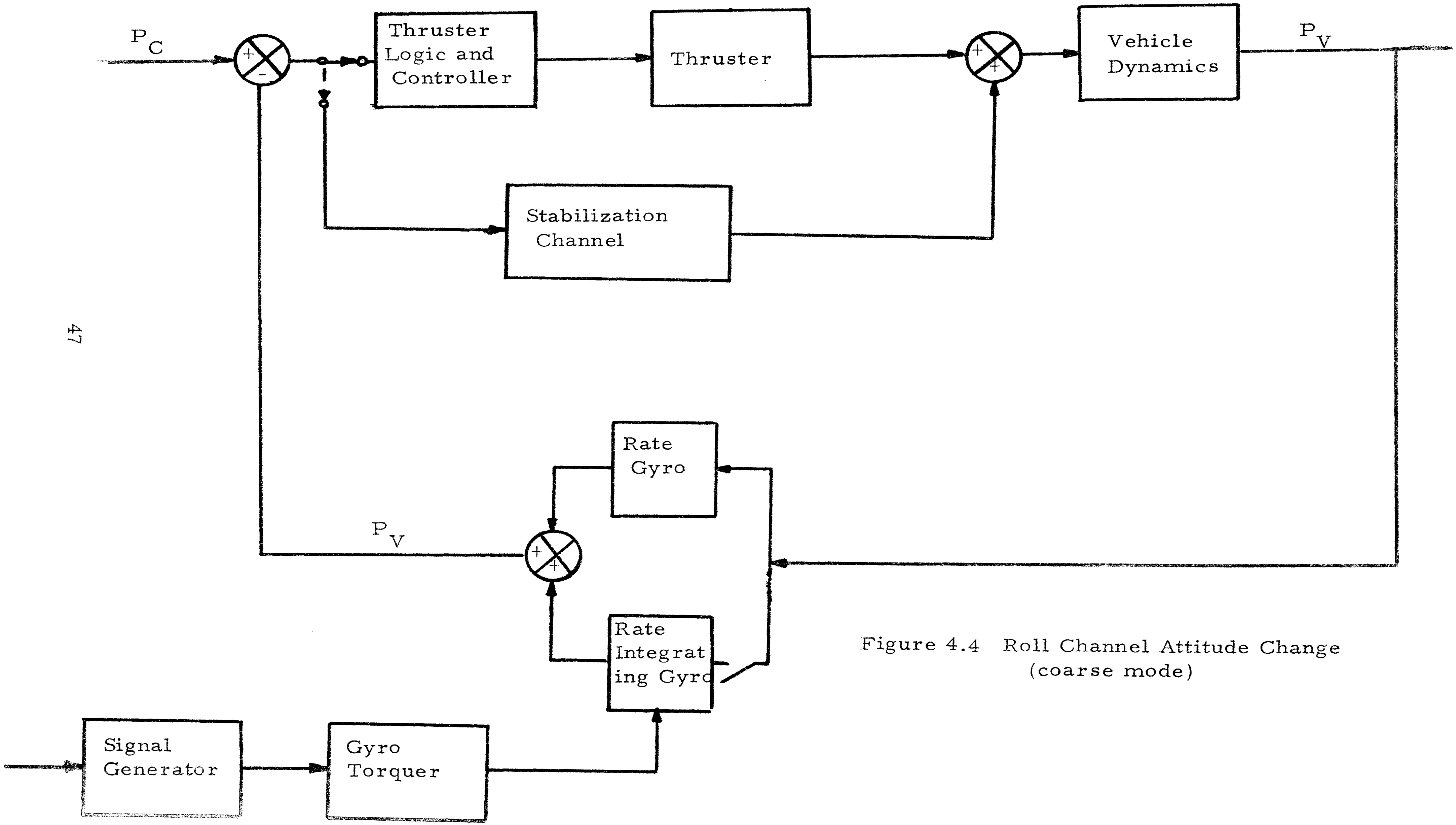


Figure 4.4 Roll Channel Attitude Change
(coarse mode)

Once the gyros are at the proper temperature, they may be zeroed and started up. Upon reaching synchronous speed, the gyros may be unlocked. The attitude sensors are now no longer dependent on external support.

The reaction wheels and control system package are then actuated.

The cold gas thruster system is now checked. Temperature and pressure are monitored until the desired values are achieved. The umbilical is then ready to be removed and REMUS is ready to undock.

4.2.2 Undocking

Undocking is accomplished by simply releasing the grips on the docking tethers and thrusting away from the docking bay. It is necessary, of course, to pan around 180 degrees with the cameras so that the operator may see where the spacecraft is going. Once away from Skylab, the longitudinal motion may be stopped and the docking tethers retracted, or REMUS may continue with the tethers extended, depending on the mission. The spacecraft may then proceed to the worksite.

The undocking velocity should be kept quite low. It is suggested that the rate be no greater than 0.1 fps.

4.2.3 Navigation and In-Flight Procedures

The biggest problem REMUS' operator may face is knowing exactly where he is with respect to Skylab. Although REMUS is equipped with stereoscopic television, changing light conditions may make pattern recognition difficult. As an aid to the operator the Skylab should be sectioned with each section bearing a code number in easily visible paint. The operator will have a set of charts showing where on the Skylab the particular section is. This enables him to know where any potential obstacles are with respect to his present position. Observing the apparent angle of the section number with respect to the television camera vertical gives the operator a check on his attitude with respect to Skylab. He then may determine not only his position, but the direction he must thrust to his next desired worksite.

Under present state-of-the-art conditions there is no extremely accurate means of obtaining range at the small distances involved in the REMUS operation. Therefore, for the present the operator must rely on stereoscopic television and the operator's own judgments. Velocities must, of course remain small relative to Skylab. Closing velocities will be no greater than 0.1 fps, while translational velocities will not exceed 0.5 fps. Further studies and simulations must be undertaken to determine whether, in fact, the operator can get a good enough 'feel' of his position to operate the REMUS safely. There are advancements in close-in ranging under development, which will be discussed in more detail. It is believed, however, for present mission requirements, visual methods and slow relative velocities will be adequate to operate the spacecraft.

The translational velocity of 0.5 fps mentioned earlier will be used for the inspection mission of Skylab's external surface and equipment. For the ATM film retrieval mission the relative velocities will be much smaller. The exact value of these velocities will be up to the operator, and may be determined by simulation.

4.2.4 Docking

Docking will be an important function of REMUS. It must be able to dock to a worksite before the manipulator arms can perform their desired task.

Initially REMUS will move to a point in space directly opposite the target area where the spacecraft must dock. The desired attitude is commanded, and the spacecraft is automatically stabilized at this attitude. A visual check is made to assure the desired attitude has been attained. The docking tethers are then turned to the appropriate pre-calculated angle and deployed slowly to a length of four feet. A visual check is again made of REMUS's attitude with respect to the docking site. When the operator is satisfied that REMUS is in the proper position, he pulses the thrusters to give a small V in the +X direction. As the spacecraft moves slowly in, the docking tethers may be seen to be out of line. The closing rate is slow enough so that the minor corrections may be made. If a large error is apparent, the closing rate may be stopped and REMUS realigned. The docking procedure is then repeated.

As REMUS approaches its docking position, the tether grips approach a set of three rings at the docking site. When the docking grips touch the rings, a solenoid switch will close the clamp and the spacecraft will be docked. The margin of error for the docking tether alignment is a radius of four inches about each ring. If this is not achieved on the first approach, another approach might have to be made.

4.2.5 Shutdown

At the end of a mission, REMUS will return to its docking bay on Skylab. Once docked, the manipulators will fasten the service umbilical. Once that is completed the attitude control system is ready to be shut down. All that is required is an off command to each component of the system. They will then return to their inactive status.

4.3 FAILURE MODES

4.3.1 Thruster Loss

REMUS can operate satisfactorily in the event of the loss of one or more thrusters.

Under normal operating conditions four thrusters are used for rotation about each axis. The loss of one of the four thrusters may be compensated for by not using its counterpart. Rotation about this axis may now be accomplished using only two thrusters.

Translation in the +x direction may be preserved under loss of a thruster, but translation in the $\pm y$ or $\pm z$ could be seriously affected by a loss of one of the thrusters used in these operations. Translations in these two directions are not critical, however, and the mission can continue with translation capabilities along the x-axis alone. Under this mode of operation more rotations must, of course, be made.

4.3.2 Rate Gyro Loss

In the event of failure of one or more rate gyros, all rate gyros may be turned off. The system is capable of functioning in their absence.

The rate integrating gyros will still be operational to give error angles. These angles can be differentiated over time on board Skylab to give angular rates. This will provide all needed information. Accuracy will suffer somewhat, but the mission can continue.

4.3.3 Rate Integrating Gyro Loss

The rate integrating gyros may also be turned off in event of failure. The rate gyros will continue to provide angular rates, which may be integrated on board Skylab to give attitude angles. Again, this method will cause decreased accuracy, but will enable a completion of the mission under way. In both cases it may be desirable to override the automatic control system, and use the information obtained directly, along with visual information.

4.3.4 Reaction Wheel Loss

The major effect of the loss of reaction wheels will be a decrease in the 'tightness' of the system. Reaction wheels provide continuous control, while thrusters can give only pulsed control under fuel conserving conditions, allowing for greater drift about the desired attitude. The loss is not serious as long as extreme care is exercised during the docking phase.

4.3.5 Communications Loss

A loss of communications may be critical if REMUS is closing with Skylab at the time of this loss. For this reason an automatic abort vector with appropriate thruster commands to stop the closing rate is stored in a logic circuit. If communications are lost during this time the appropriate thrusters are fired for a length of time sufficient to stop all closing rates. Once communications are resumed REMUS may be recovered. The abort mode is manually switched off when REMUS is not closing with Skylab.

Loss of communications does not affect the automatic attitude control system.

4.4 ADDITIONAL CONSIDERATIONS

4.4.1 Moment of Inertia Changes

ATM film packs weight 100 to 200 pounds. While REMUS is carrying these film packs, the moments of inertia and principal axes will be changed. The moment of inertia changes will be rather large, but the principal axis changes will be relatively small, if the film packs are carried in the racks provided on top of REMUS. For this reason it is believed that REMUS will be able to handle the changes involved.

Pilot training and simulation should be able to compensate for any problems in control that occur. The actuators are designed so that they will be able to handle the expected changes in moments of inertia.

4.4.2 Development of Close-In Ranging

The present state-of-the-art does not provide an accurate means of determining small ranges. This is why REMUS relies heavily on stereoscopic television and man in the control loop. It is realized that this is not the ideal situation, and that it is desirable to develop a better and more accurate means of finding short ranges.

Work is now being done at ITT on a laser radar. It seems that this system will be a promising one when completed. Weight, power, and size requirements might preclude use on REMUS, however.

Another possibility is development of a visual range finder to be used in conjuction with the television camera system.

REFERENCES

1. Adamski, Donald, et al, "Unmanned Teleoperator Spacecraft Technology," AIAA Paper No. 69-1067, 1969.
2. Blakelock, John H., Automatic Control of Aircraft and Missiles, John Wiley and Sons, Inc., New York, 1965.
3. Cannon, Robert H., Jr., "Some Basic Response Relations for Reaction Wheel Attitude Control", ARS Journal, January, 1962.
4. Dinter, Henry A., Inertial Sensors Theory and Application, Honeywell Aerospace Division, Minneapolis, 1967.
5. Fernandez, Maneul, and Macomber, George R., Inertial Guidance Engineering, Prentice-Hall International, London, 1962.
6. Greensite, Arthur L., Analysis and Design of Space Vehicle Flight Control Systems, Spartan Books, New York, 1970.
7. Hallum, C. E., et al, "New Functional Approaches for Redundant Inert Gas Thruster Systems," AIAA Paper No. 69-843, 1969.
8. O'Connor, B. J., and Morine, L. A., "A Description of the CMG and its Application to Space Vehicle Control", AIAA Paper No. 67-589, 1970.
9. Parvin, Richard H., Editor, Principles of Guided Missile Design, D. Van Nostrand Company, Inc., Princeton, N. J., 1962.
10. Phillips, James P., "Control Moment Gyro Characteristics and Their Effects on Control System Performance," AIAA Paper No. 68-875, 1968.
11. Singer, S. Fred, Editor, Torques and Attitude Sensing in Earth Satellites, Academic Press, New York, 1964.

5
COMMUNICATION SUBSYSTEM

5.0 INTRODUCTION

The Teleoperator, to simulate astronaut extravehicular activities (EVA) and perform specified tasks, must maintain a continuous two-way communication link with Skylab. This section describes the characteristics of the Communication Subsystem. Further technical discussion of the subsystem appears in Appendix D.

5.1 REMUS SYSTEM REQUIREMENTS

The design of the Communication Subsystem must satisfy the following requirements:

1. Provide continuous two-way communications between Teleoperator and Skylab
2. Be compatible with Skylab
3. Must transmit the following signals to Skylab

DATA

Subsystem	Number	Format	Modulation Process
Manipulators	28	High Level	FM/AM
Manipulators	21	High Level	PAM/FM/AM
Power	4	High Level	PAM/FM/AM
Attitude & Control	6	High Level	FM/AM
Attitude & Control	5	High Level	PAM/FM/AM
Structures	36	Differential	PAM/FM/AM
Thermal	4	High Level	PAM/FM/AM
Video	2	Analog (4MHz)	AM

4. Must transmit the following signals to the Teleoperator:

CONTROL

Subsystem	Number	Format	Modulation Process
Manipulators	28	High Level	FM/AM
Attitude & Control	6	High Level	FM/AM
Thruster	1	Coded	PCM-FSK/AM

COMMAND

Subsystem	Number	Format	Modulation Process
Attitude & Control	6	Bi-Level	PCM-FSK/AM
Power	4	Bi-Level	PCM-FSK/AM
Video	12	Bi-Level	PCM-FSK/AM
Manipulators	30	Bi-Level	PCM-FSK/AM
Structures	1	Bi-Level	PCM-FSK/AM
Thermal	9	Bi-Level	PCM-FSK/AM
Communications	10	Bi-Level	PCM-FSK/AM

Operation close to Skylab creates interference problems that dictate the use of the lowest practical frequency. A design tradeoff between antenna size, bandwidth efficiency, and information bandwidth show amplitude modulation in the VHF band to be most desirable.

The REMUS system operates in the duplex mode to give continuous two way communications. All subsystems are constructed for complete redundancy to meet reliability constraints.

5.2 TELEOPERATOR COMMUNICATIONS SYSTEM SPECIFICATIONS

5.2.1 Teleoperator System Requirements

1. Manipulator control signals from Skylab must be continuously received, decoded, and distributed.
2. Spacecraft operational commands from Skylab must be received, decoded, and distributed.
3. TV signals, manipulator-feedback signals, and engineering telemetry data must be continuously transmitted to Skylab.
4. Carrier frequencies, RF bandwidths and signal power levels must be compatible with subsystems and designed to have minimum interference with the Skylab communications subsystem.
5. Operating range will be less than one statute mile.
6. Umbilical hardline will be used for engineering telemetry and operational commands during Teleoperator refurbishment.

5.2.2 Teleoperator Communications Subsystem Description

The functional design based on the system and subsystem requirements is shown in Figure 5.1. The Command and Control Subsystem receives, processes and distributes manipulator control signals, attitude and control signals, and spacecraft operational commands. The Data Management Subsystem multiplexes one TV signal, twenty-eight manipulator-feedback signals, six attitude and control signals, and engineering telemetry into one composite baseband signal. The other TV signal is transmitted directly.

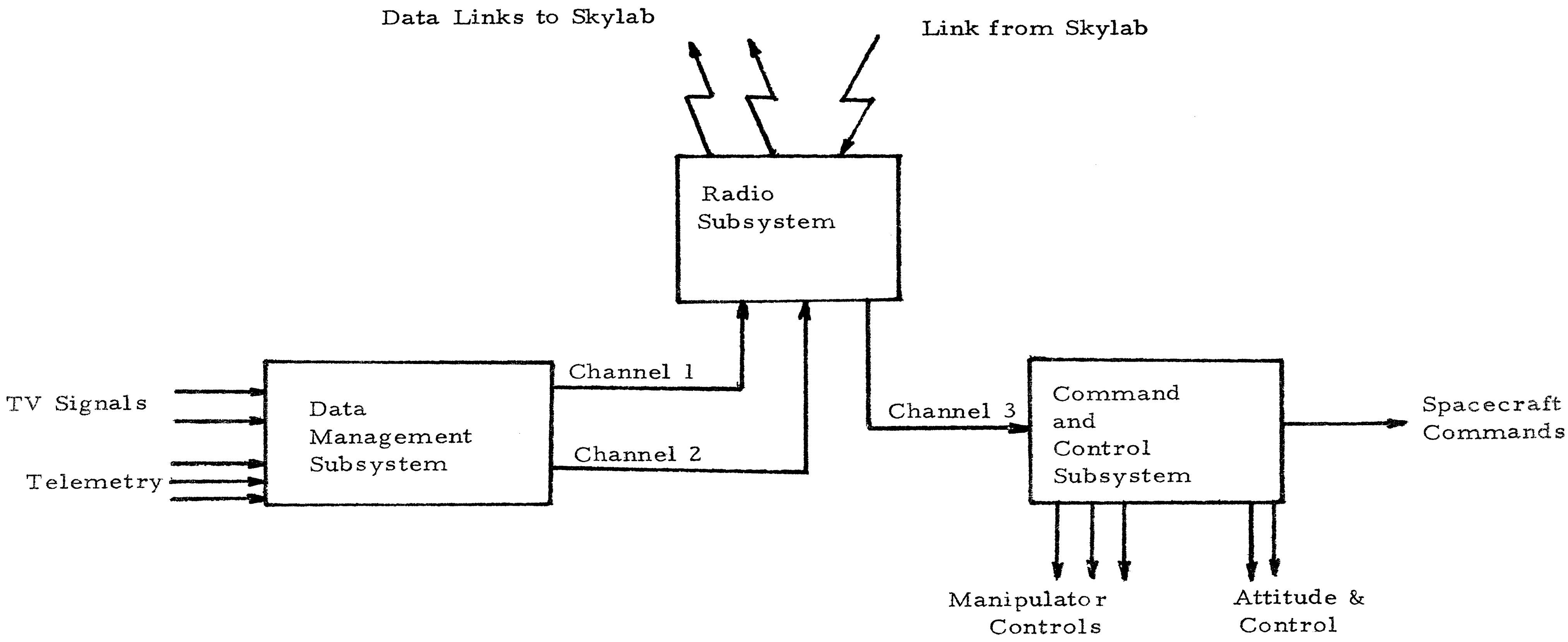


Figure 5.1 Teleoperator Communication Subsystem Functional Flow

5.2.3 Teleoperator Radio Subsystem

The Radio Subsystem is designed to receive one RF signal and transmit two RF signals simultaneously. The basic subsystem shown in Figure 5.2 consists of two omni-directional antennas, two AM transmitters, two command receivers and RF switches. The frequency assignments are Channel 1--200 MHz, Channel 2--211 MHz and Channel 3 (command and control channel)--193 MHz.

A. Omni-Directional Antennas

To provide uniform coverage two omni-directional turnstile antennas are positioned on opposite sides of the spacecraft. Due to mutual interference only one antenna at a time will be operational. Antenna selection will be either manual from Skylab or automatic on the Teleoperator in the event of loss of received command signal.

Specifications

1. 10% bandwidth at 200 MHz
2. VSWR at least 2:1
3. Withstand launch environment

B. AM Transmitter

1. Output power 0.5 watt
2. Input bandwidth to modulator max 4.250 MHz

C. AM Receiver

1. IF bandwidth = 340 KHz
2. Sensitivity = -120 dbw
3. AGC essential
4. Overload protection

5.2.4 Teleoperator Command and Control Subsystem

A block diagram of the Command and Control Subsystem is shown in Figure 5.3. The subsystem receives the following signals from the Radio Subsystem:

1. Command Channel--PCM/FSK command signal centered at 10 KHz. Commands are 12 bit words sent at 120 bps.
2. Control Channel--frequency multiplexed composite signal containing all control signals consisting of:
   a. Thirty-four manipulator/attitude and control FM subcarrier signals. Subcarriers start at 101 KHz with 2 KHz spacing between adjacent subcarriers. The last subcarrier is at 167.0 KHz.
   b. One PCM/FSK thruster control signal centered at 169 KHz. Bit rate is 100 bps.

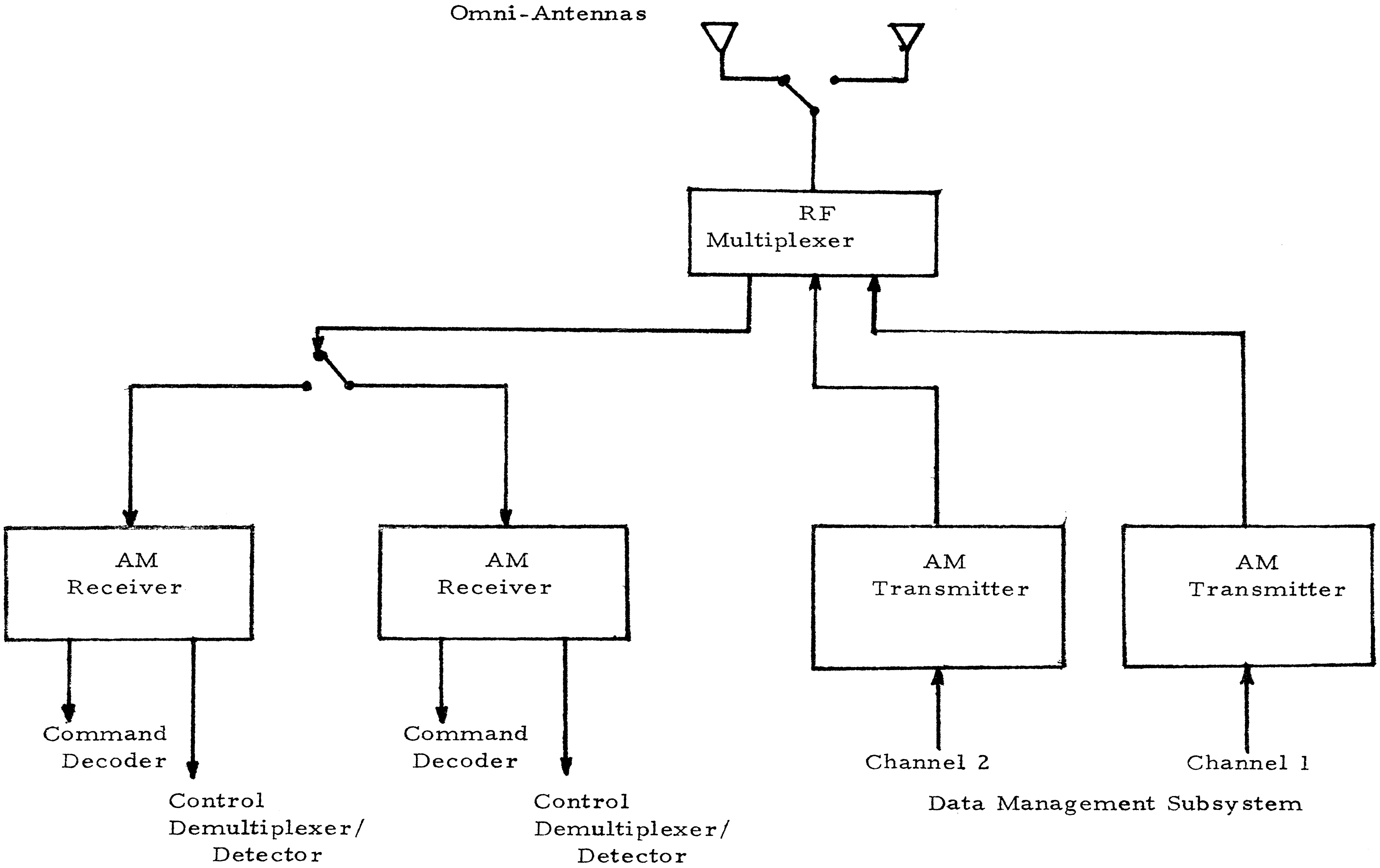


Figure 5.2 Teleoperator Radio Subsystem

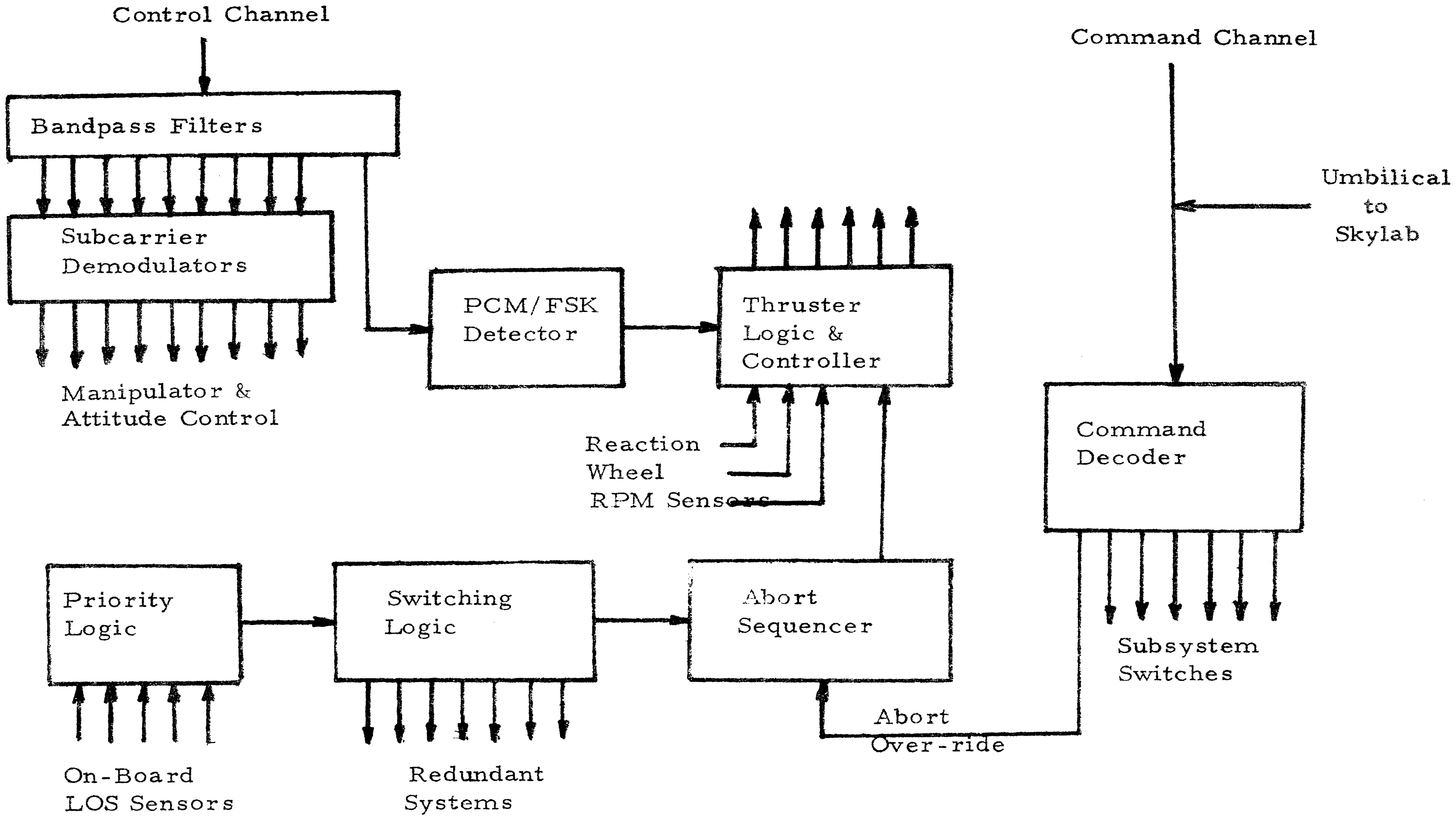


Figure 5.3 Teleoperator Command & Control Subsystem

The command decoder processes coded commands and activates the proper subsystem switches. All commands are real time and contained in coded 12 bit words consisting of 1 bit synchronization, 1 bit parity, 7 bits command addressing and 3 bits information. During Teleoperator refurbishment commands are sent to the command decoder via an umbilical from Skylab.

The band pass filters frequency demultiplex the control channel into thirty-five separate subcarrier signals. Thirty-four of these channels contain manipulator and attitude control signals and are FM demodulated amplified and then sent to the subsystems. The other subcarrier is the PCM/FSK thruster control signal, which is detected before entering the Thruster Logic and Controller (TLC). The TLC performs three functions:

1. Receives, decodes and effects real-time thruster firing via the control channel.
2. Receives reaction wheel tachometer readings to automatically desaturate reaction wheels, by proper thruster firing.
3. Receives abort command from abort sequencer to effect abort thrust during rendevous phase in case of loss of signal (LOS).

Command and control communications are necessary at all times. On board, LOS sensors at different levels in the system are fed into the priority logic which detects the defective subsystem and effects switching to a redundant subsystem via the switching logic. If on-board switching is unable to correct the LOS condition the abort sequencer sends an abort thrust command to the TLC. An abort override command is provided via command decoder to disable the abort function.

5.2.5 Teleoperator Data Management Subsystem

The Teleoperator Data Management Subsystem combines all signals being sent to Skylab into two channels. The design is completely redundant for reliability. Force feedback, gyro outputs, and engineering telemetry are combined with the TV No. 1 signal to form a composite baseband signal of 4.25 MHz on Channel 1. This channel, along with the unmultiplexed TV No. 2 signal on Channel 2 is delivered to the Radio Subsystem for transmission. A block diagram of the Data Management Subsystem is shown in Figure 5.4.

Seventy channels of engineering telemetry are commutated and pulse amplitude modulated in the PAM commutator. The output of this device is 28 pulses per second. This signal comprises one input into the voltage controlled oscillators.

The voltage controlled oscillators, or VCO's, frequency modulate the incoming signals on a subcarrier at the proper level for multiplexing. One VCO is required for each input. Twenty-eight signals from the manipulators,

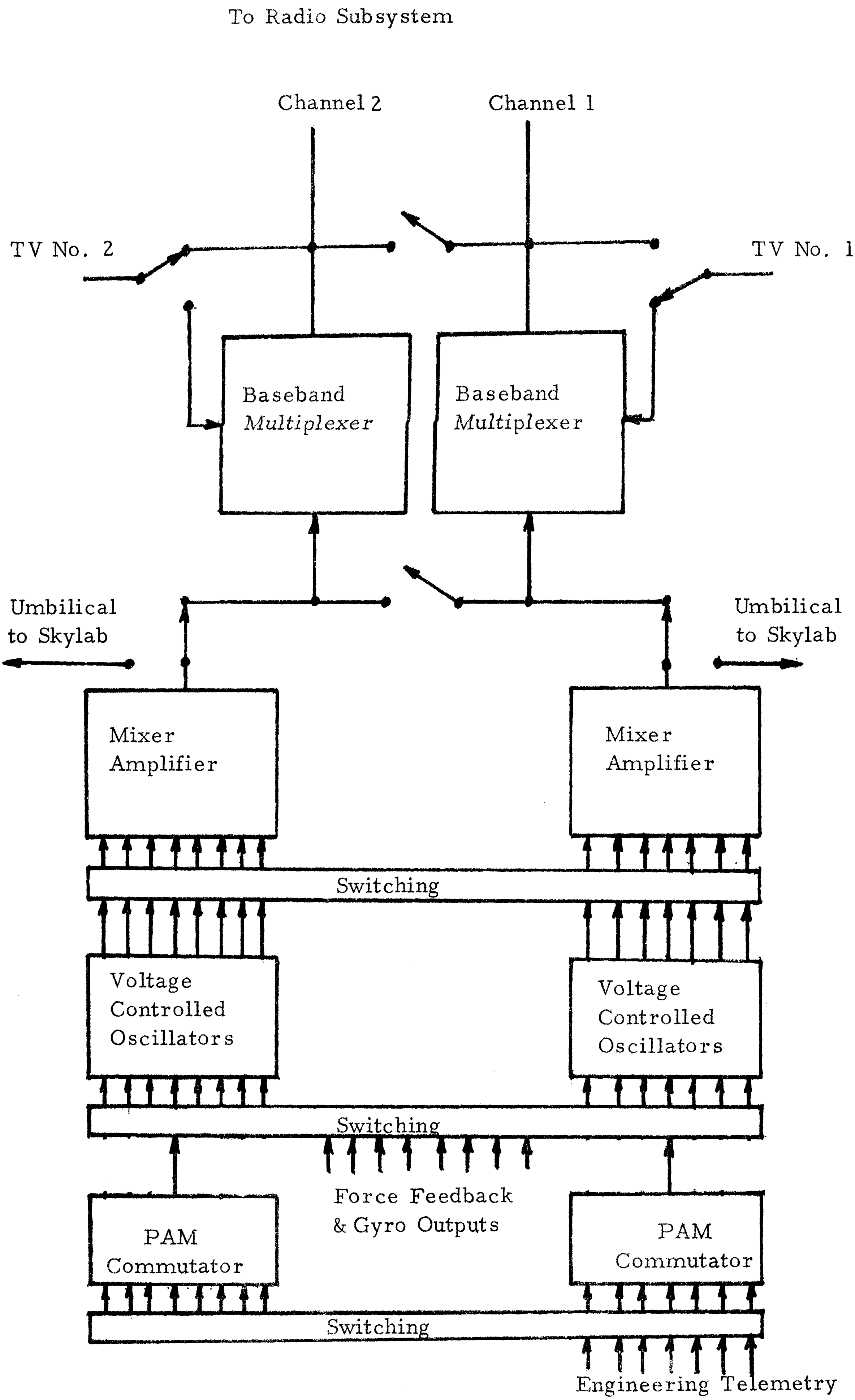


Figure 5.4 Teleoperator Data Management Subsystem

six gyro outputs, and the commutated telemetry comprise the 35 inputs into the VCO's. The 35 VCO's required for frequency modulation have subcarrier frequencies from 4.181 MHz to 4.249 MHz equally spaced by 2 KHz.

The 35 signals from the VCO's are then delivered to a mixer amplifier for conditioning before being multiplexed with the TV signal. The mixer combines the 35 inputs into a single output which is then amplified and multiplexed with the TV signal.

When docked for refurbishment, hardline communcation is maintained by the umbilical. No video is transmitted during this time, but all other information can be delivered to Skylab.

In that the design of the Data Management Subsystem is completely redundant, any component failure will not impair full scale operation. A maximum of three component failures can be tolerated with no degradation in data handling capability.

5.3 SKYLAB COMMUNICATIONS SUBSYSTEM SPECIFICATIONS (REMUS IMPLEMENTATION)

5.3.1 Skylab Communication Subsystem Description

Some implementation to Skylab will be necessary to support the REMUS system. This interface will center around the command console. Figure 5.5 gives the functional flow through the Skylab Communications Subsystem.

The Radio Subsystem receives the signal from the Teleoperator and distributes the TV signals to the console for display and the telemetry, attitude and control signals, and force feedback signals to the Data Processing Subsystem for further demodulation and buffering. The Data Processing Subsystem demodulates the frequency multiplexed and PAM/FM signals and delivers them to the console. The Command and Control Initiation Subsystem encodes commands and delivers commands and control signals, either computer or console originated, to the Radio Subsystem for modulation.

5.3.2 Skylab Radio Subsystem

The Radio Subsystem, designed to receive two RF signals and transmit one RF signal simultaneously, is shown in block diagram form in Figure 5.6. The received signals, Channel 1 and Channel 2, have center frequencies of 200 and 211 MHz respectively. The frequency assignment for the command and control channel (Channel 3) is 193 MHz.

The AM receivers are broadband demultiplexers and AM demodulators. After demodulation, the TV signal is stripped off the composite baseband signal by the use of a low-pass filter. This TV signal is delivered

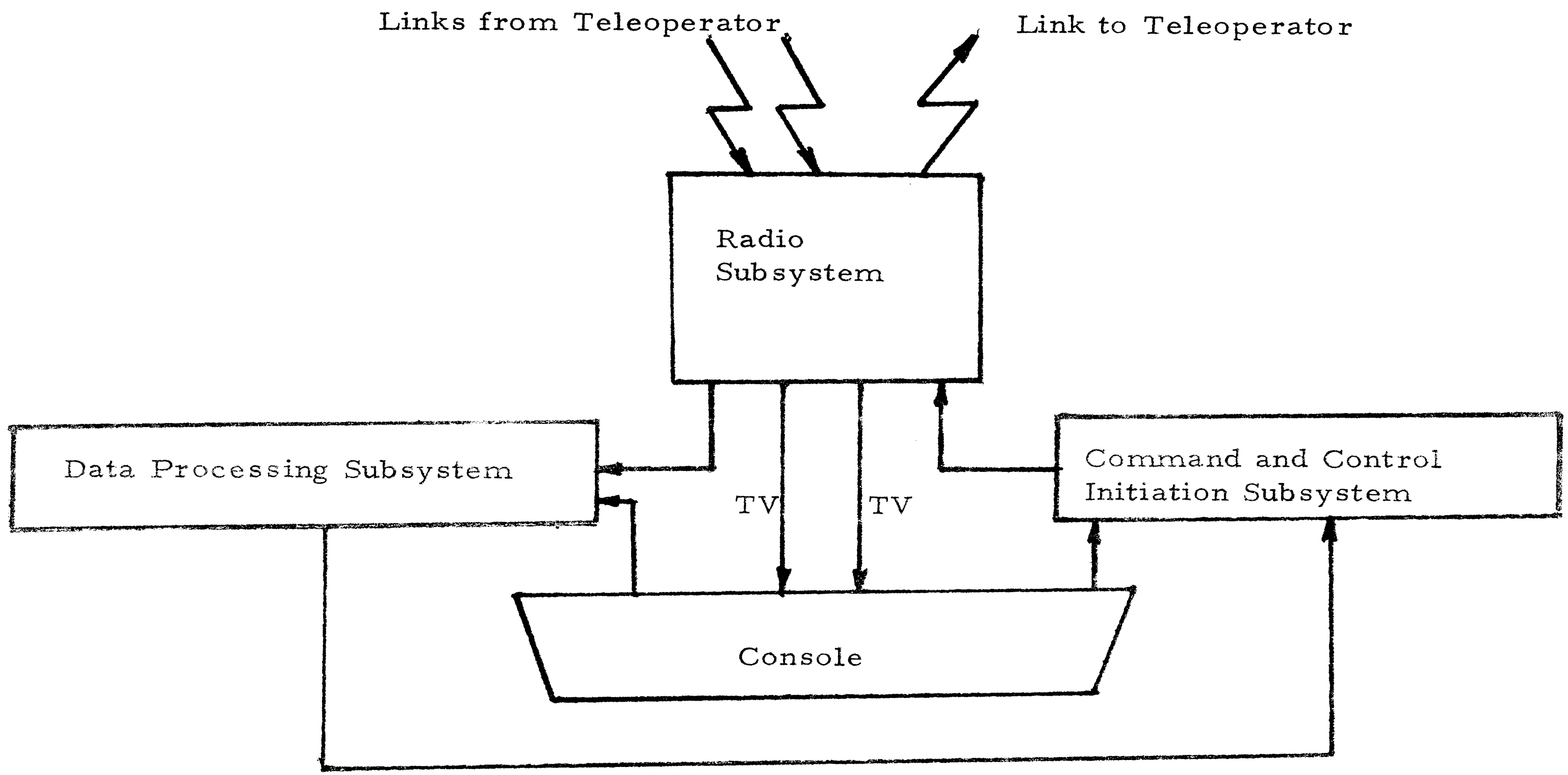


Figure 5.5 Skylab Communication Subsystem Functional Flow
(REMUS Implementation)

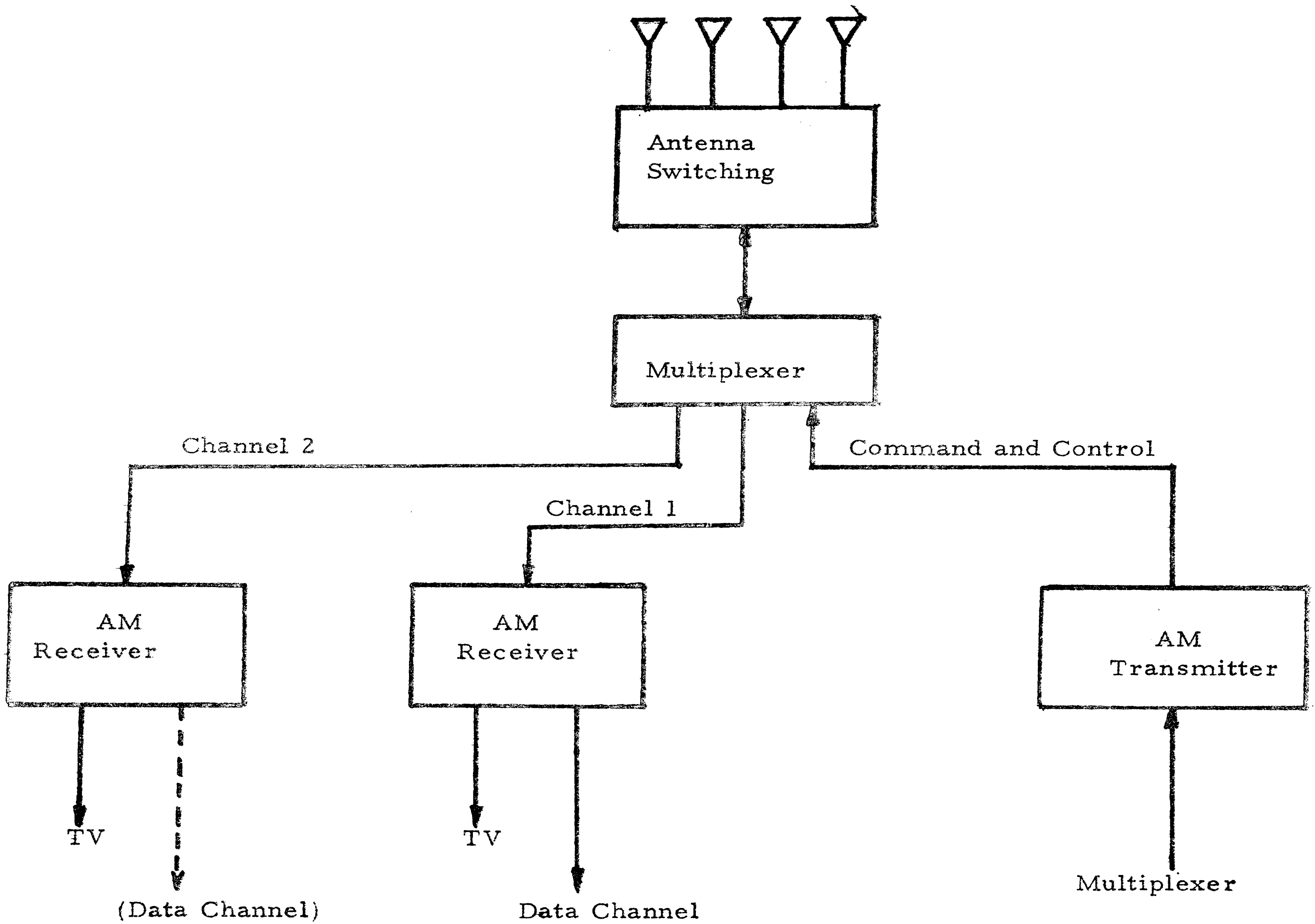


Figure 5.6 Skylab Radio Subsystem

directly to the console. The outgoing data channel is sent to the Data Processing Subsystem. Either AM receiver has full capacity to handle the multiplexed signal. This affords redundancy, and makes switching unnecessary when Channel 2 is the multiplexed channel (backup mode from the Teleoperator).

The AM transmitter operates at an output power of 0.5 W, with input bandwidth of 170 KHz. The input to the transmitter is a composite channel containing 34 frequency multiplexed signals for control and two PCM/FSK modulated signals in the NRZ (non-return to zero) format.

The AM modulated signal passes through the multiplexer to the antenna switching control, where it is delivered to the proper antenna. Antenna switching is controlled at two levels. Certain areas of Skylab are better covered by certain blocks of antennas. The operator, knowing the particular area in which the Teleoperator will be operating, can choose the correct antenna block by activating switches on the console. Once a given block of antennas is chosen, automatic switching will control final selection of the proper antenna for a given position of the Teleoperator. A description of antennas for the REMUS system appears in Appendix D.

5.3.3 Skylab Data Processing Subsystem

A block diagram of the Skylab Data Processing Subsystem is shown in Figure 5.7. The function of the Data Processing Subsystem is to route incoming data to the proper destination. The multiplexed data channel is separated into 35 signals by bandpass filters. These signals are then delivered to subcarrier demodulators to recover the transmitted signal.

The telemetry channel is sent to the PAM decommutator for further demodulation and decommutation. This process recovers the 70 telemetry signals.

Further conditioning is needed for attitude and control signals and telemetry. These signals, processed and/or stored digitally in computer banks, must be digitized using analog to digital converters.

Finally, all signals must be conditioned to the proper levels for the various components they drive. Therefore, signal conditioning is provided to buffer the signals.

The force feedback signals are delivered directly to the master arms located at the console. Also, some direct read-out telemetry is sent to the console. The telemetry and attitude control signals that must be processed are bused to memory banks and logic circuity. The console interacts with the computer through this bus, also. The computer interacts with the console and the Command and Control Initiation Subsystem through another bus.

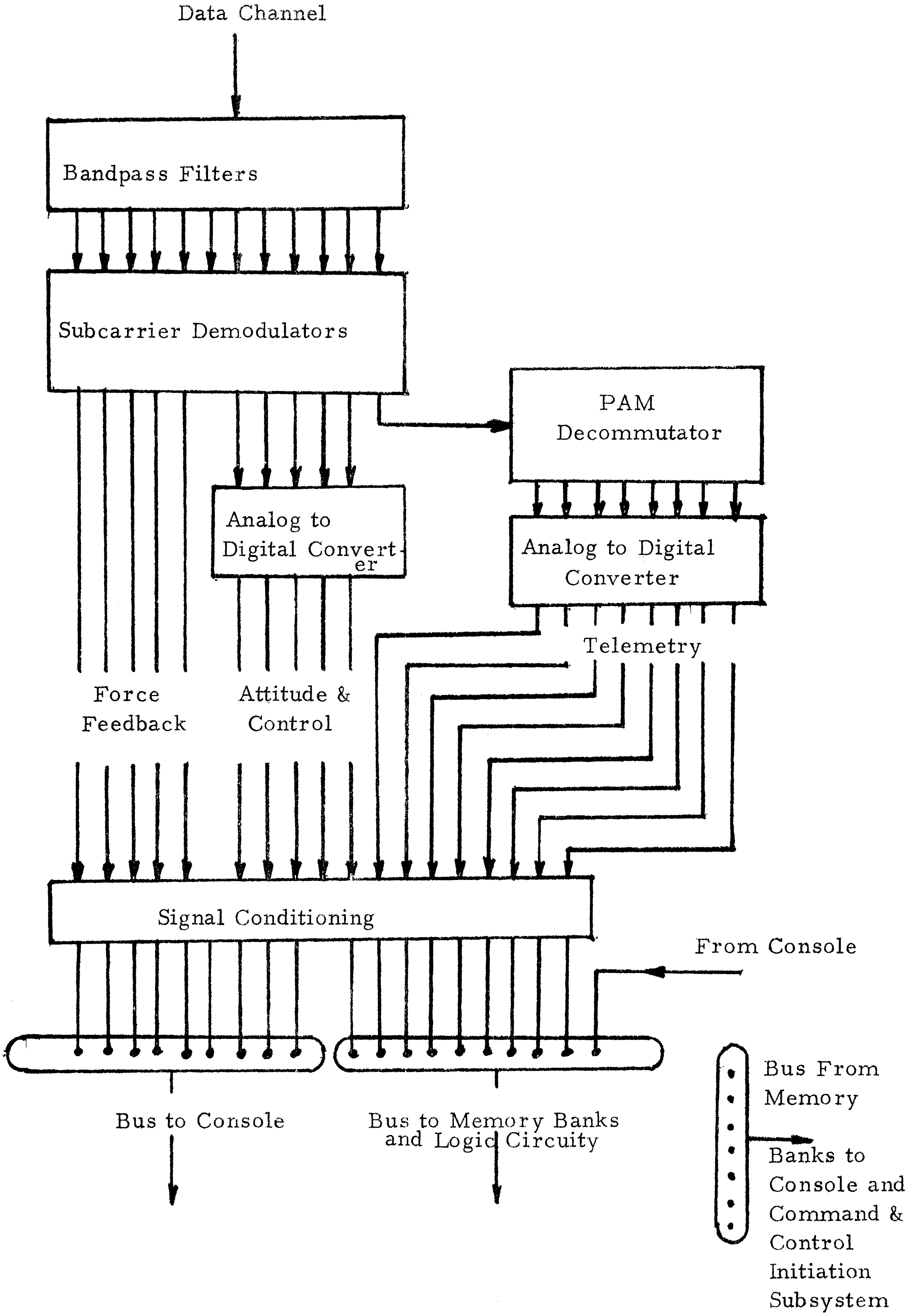


Figure 5.7 Skylab Data Processing Subsystem Block Diagram

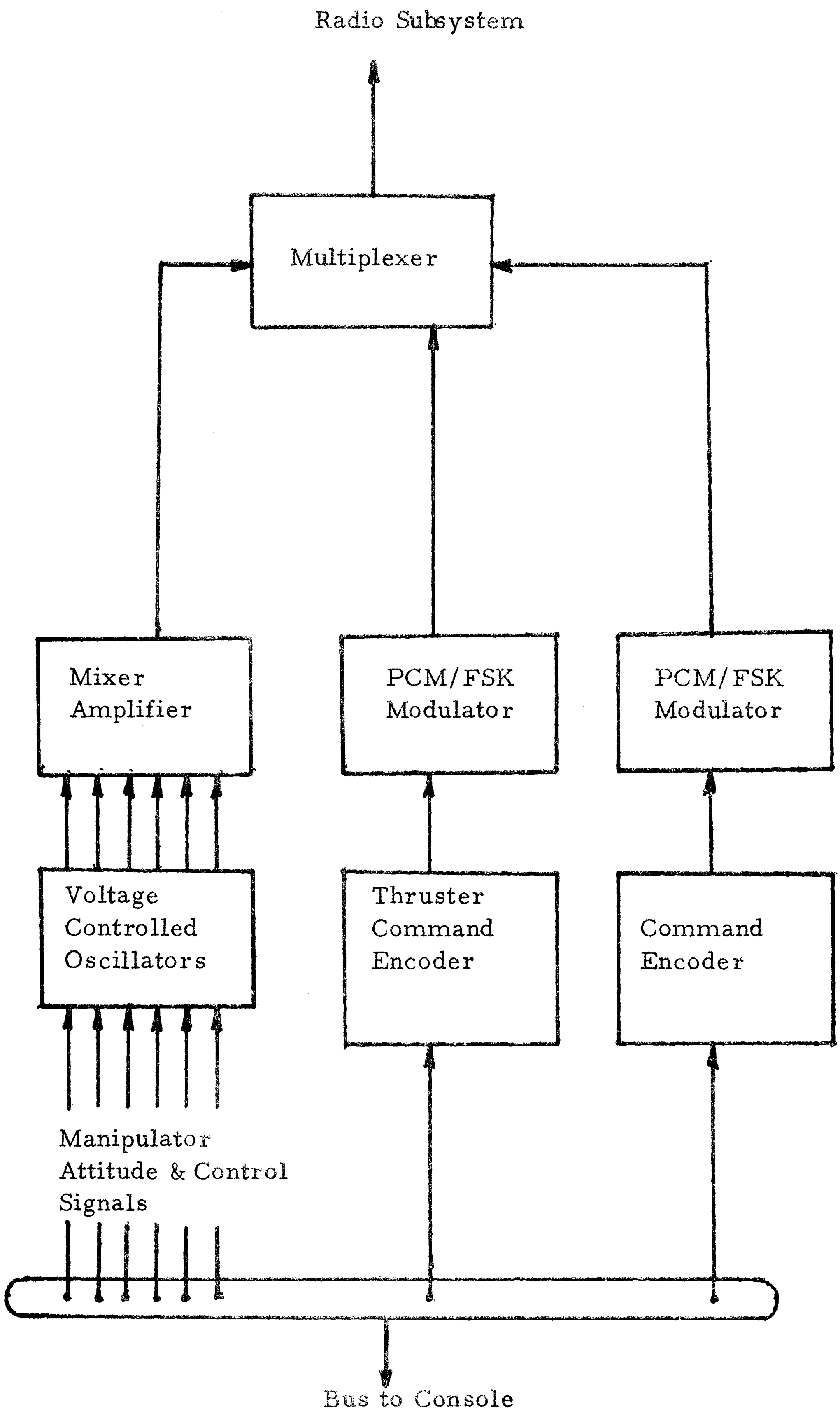


Figure 5.8 Skylab Command & Control Initiator

5.3.4 Skylab Command and Control Initiation Subsystem

A basic block diagram of the Command and Control Initiation Subsystem is shown in Figure 5.8. Thirty-four manipulator control and attitude control signals originating from the console and the computer drive voltage-controlled oscillators with subcarriers spaced 2 KHz from 101 KHz to 167 KHz. The output of the VCO's are fed into a mixer amplifier for proper signal conditioning.

The thruster command encoder generates the correct digital thruster code from the thruster controller on the console. The generated code consists of an 8 bit word. The bit stream out of the encoder is PCM--NRZ at 100 bps which is FSK modulated at 169 KHz.

Command signals from console switches are coded into a 12 bit word by the command encoder. The word is comprised of 1 bit synchronization, 1 bit parity, 7 bits command address and 3 bits information. The bit rate out of the encoder is 120 bps which is FSK modulated at 10 KHz.

The outputs from the two PCM/FSK modulators and the mixer-amplifier are then frequency-multiplexed into a composite baseband signal to be transmitted by the Radio Subsystem.

5.3.5 Skylab Command Console

The console must be designed to integrate the operator into the REMUS system. Telemetry data flow to the console will be kept to a minimum in order not to overburden the operator.

Warning lights will be used to indicate malfunctions. Current telemetry values, displayed on a digital readout, are available to the operator on request.

REFERENCES

1. A Study for a Teleoperator Flight Experiment, Vol. 1, SD Proposal N-22042, General Electric Space Systems Organization, Valley Forge, Pa., 29 May 1970.
2. Elliot L. Greenberg, ed., Handbook of Telemetry and Remote Control, McGraw-Hill Book Company, New York, 1967.
3. Handbook on Radio Frequency Interference, Vol. 1, pp 4-64, Frederick Research Corporation, Wheaton, Md., 1962.
4. Nichols, M. H., and Rauch, L. L., Radio Telemetry, Wiley & Sons Publishing Company, New York, 1956.
5. Rauch, L. L., Aerospace Engineering 485 (Communications Systems), Class Notes, Winter Term, 1970.
6. Selection of Systems to Perform Extravehicular Activities, Vol. 2 (Final Report), Matrix Research Company, Huntsville, Ala., 9 April 1970.
7. Skylab I - Systems Description Document, Martin Marietta, Denver Division, Denver, Col., March 1970.
8. Study of Teleoperator Flight Experiment - Mid-Term Review, General Electric Space Systems Organization, Valley Forge, Pa., 6 October 1970.
9. Study of Teleoperator Flight Experiment (NAS9-11067). General Electric Space Systems Organization, Valley Forge, Pa., 1970.

6
POWER

6.1 INTRODUCTION

All the Teleoperator electrical loads will be powered by a secondary storage battery system onboard the Teleoperator. In view of the requirement for a present state-of-the-art design, three other types of power systems were also considered before selecting the chemical storage battery system. The first type considered was the solar cell system which was eliminated because the body area of the Teleoperator is too small for body solar cells, and large solar panels or paddles would greatly reduce maneuverability. A second type considered was the RTG system which was rejected because of high heat dissipation, high cost ($10,000 to $50,000 per watt), and radiation problems. Also the fuel cell type system was considered, but rejected because of its large volume and unproven reliability over long operating life. The chemical storage battery type system was considered the optimum choice, it has proven high reliability, high energy density for short missions, compactness, lower cost, and requires no maintenance except recharging.

6.2 POWER REQUIREMENTS

Power requirements for the Teleoperator will vary greatly from mission to mission, and for any given mission will vary with such things as skill of the operator, illumination needed, length of time to complete tasks, etc. For this reason it is not possible to obtain the exact power profile for a mission, manipulator power in particular will be so erratic as to defy prediction. However average power requirements and peak power requirements have been obtained and the average power profile for the maximum capability mission of 10 hours is shown in Figure 6.1 Here it is assumed that 8 of the 10 mission hours take place at the worksite, the other 2 are used in translation. The average power requirements along with the peak power requirements are shown in the following table. Also listed are the voltages needed in the subsystems.

Subsystem	Average Power	Peak Power	Voltage
Manipulators	50 watts (0 watts during translation)	630 watts	28 v
Attitude and Control	50 watts (70 watts during translation)	211 watts 312 watts during translation)	28 v & 26 v. ac. 3 phase
Video	55 watts	70 watts	28 v
Communications	35 watts	60 watts	28 v
Thermal	5 watts	45 watts	28 v & 6 v
Structures	none	none	6 v
Totals	195 watts (165 watts during translation)	1016 watts (487 watts during translation)	

Total energy needed by subsystems during this 10 hours mission is 1890 watt-hours. If 10% regulation and distribution losses are assumed the batteries will be discharged 52% on the 10 hour mission.

6.3 COMPONENTS

6.3.1 Batteries

The source of electric power for the Teleoperator will be two high capacity Silver-Cadmium storage batteries. Two batteries were chosen to allow some redundancy in case of failure. Each battery will be composed of 26 cells making the nominal plateau voltage 28.6 volts per battery. Each cell will be rated at 70 ampere-hours and the batteries will nominally store a total of 4004 watt-hours. As mentioned above the batteries will be discharged a maximum of 52% during a 10 hour mission. Depth of discharge of course will vary slightly with rate of discharge, temperature, and age.

Silver-Cadmium type batteries were chosen for the Teleoperator from among the three types currently used on space vehicles, Nickel-Cadmium, Silver-Cadmium, and Silver-Zinc. Typical weight and cycle life values for these types are:

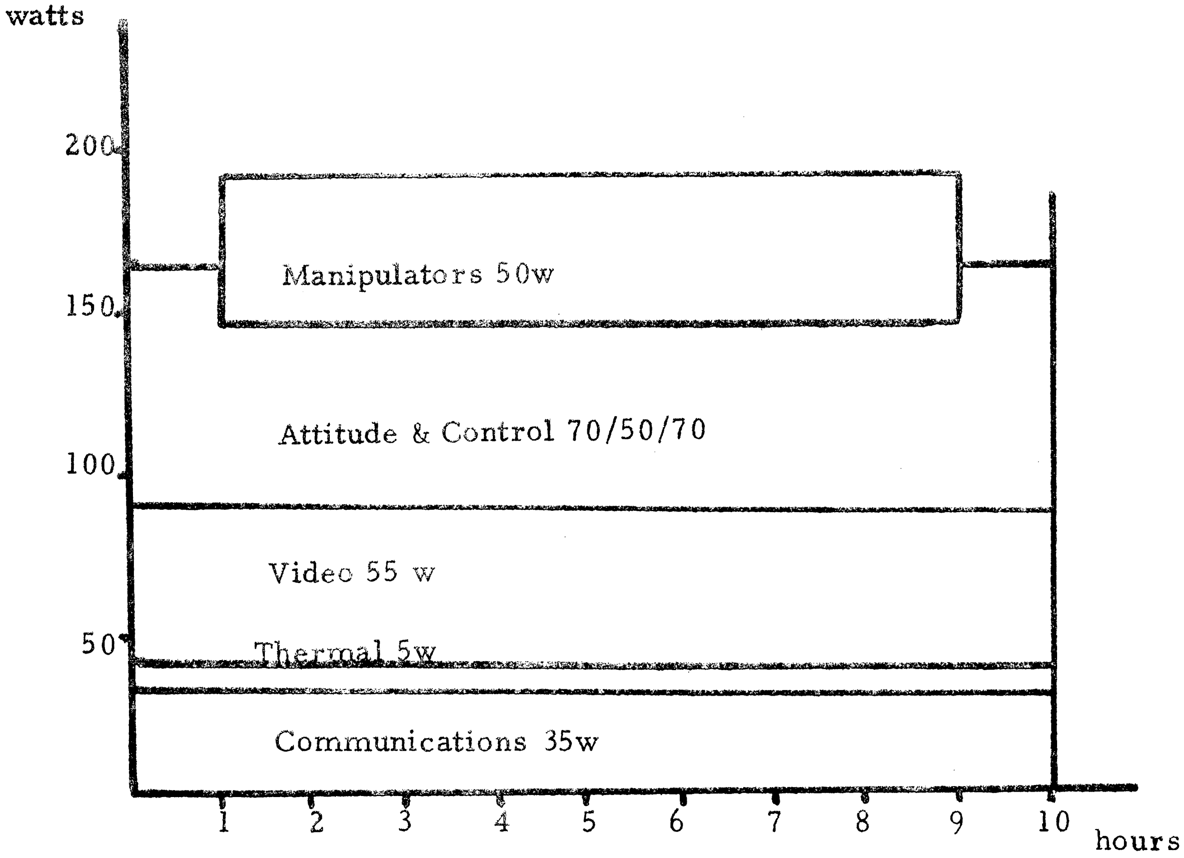
	Ni-Cd	Ag-Cd	Ag-Zn
Weight for 4000 w-hrs	280 lbs	136 lbs	100 lbs
Cycles at 50% discharge	4000	600	100
Cycles at 75% discharge	2000	300	

From the weight standpoint, Silver-Zinc is lightest and most desirable, the cycle life could be expected to be about 100 cylces. However if a few deep discharges were encountered this number would be drastically reduced. For only 36 more pounds of weight, the cycle life can be extended beyond any reasonable risk of cycle failure so Silver-Cadmium batteries were chosen. Even though this Skylab mission will require very few cycles and Silver-Zinc would probably be adequate, the value of the Teleoperator as a prototype is greatly enchanced by this high cycle capability.

Battery and cell specification are found in Appendix E. These specifications show the batteries will weigh 68.3 lbs each and occupy 834 cu in each.

6.3.2 Regulation

Voltage regulation will be accomplished through one of two redundant, interchangeable voltage regulator units. These units will hold subsystem voltage at 28 volts $\pm$ 2% except in those few cases where a lower voltage is necessary. The regulator units will have separate circuits for each subsystem, thus minimizing interaction between subsystems. The regulators used will be



Note first and last hours are assumed translation.

Figure 6.1 Average Power Profile

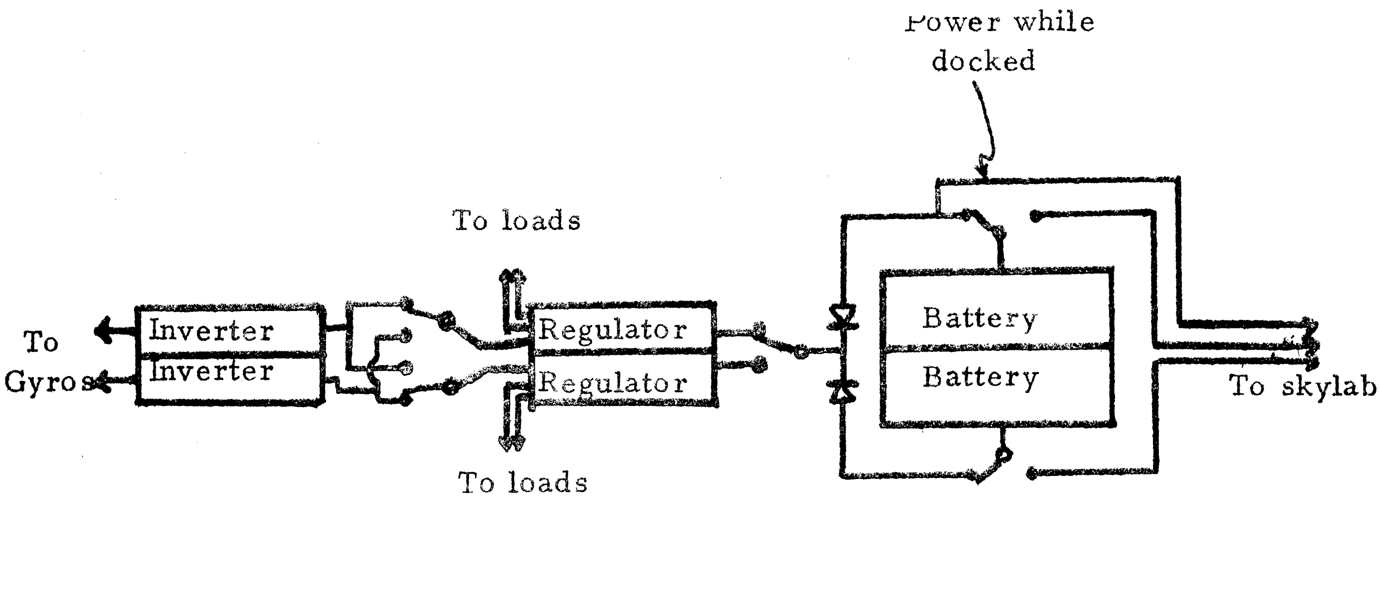


Figure 6.2 Power System Schematic

the series dissipative type for high efficiency, good regulation and simplicity. Regulator unit total capacity will be at least 400 watts continuous and 2000 watts peak each. Their efficiency is calculated in Appendix E and found to be 96% during discharge plateau. Weight and size are also found in Appendix E.

Other types of regulators were considered, the shunt regulator was considered but rejected because of its low efficiency. Switching regulators and Pulse Width Modulated Converters were considered but rejected because of their lower stability and requirements for large filters.

Another regulating component needed in the electric power system is a 3-phase inverter to drive the gyro spin motors. Two inverters will be provided, one as a backup. Both will be the solid-state type. Loading on the inverter will be a constant 23 VA at 26 v, 3 phase, inverters will have at least 50 VA capacity. Inverter package weight and size are located in Appendix E.

6.3.3 Switching and Protection

Switching on command from the master control panel will be provided to switch either battery off the line in case of failure. Or, in case of regulator or inverter failure, power will be switched to the standby regulator unit or to the standby inverter. Also, switching will be provided for changing from a discharge to a charge mode after docking. All switches should be capable of handling about 100% more load than they actually will be subject to, for reliability.

Fault and overload protection will be provided for on all subsystems by means of bi-metallic strips which open circuits when overheated. These strips operate on the thermostat principle and automatically reclose upon cooling. Under-voltage protection on the cameras will also be provided by means of solenoid relays which open the camera circuit if delivered voltage drops below 24 volts.

A schematic of the electric power system is shown in Figure 6.2.

6.4 SKYLAB INTERFACE

Skylab will interface with the Teleoperator's electric power system for three purposes, battery charging, system monitoring, and switching commands.

The battery charging operation will be done by a hardwire umbilical from two battery chargers located inside the Airlock Module. The umbilical will be connected to and disconnected from the Teleoperator by the manipulator arms after docking. The umbilical will also supply cold gas for refueling, a communications link, and housekeeping power. The dual chargers provide a backup for themselves, if one charger fails the other can recharge both batteries, one after the other. Slightly over 40 volts will be needed to charge the batteries and charging current is to be 4.0 amps per battery. End-of-charge will be detected by a sharp voltage rise to 1.55 or 1.60 volts per cell or 40 volts per battery, thus overcharge can be prevented. After end-of-charge is reached, trickle charge will be maintained if long storage is anticipated. In no case will it take longer than 10 hours to reach end-of-charge. Usually it will be reached much sooner, depending on depth of discharge.

Monitoring and switching will be done through the communications subsystem. Monitoring of two battery currents, two battery voltages, and two battery temperatures must be done. The battery temperatures will be displayed with the rest of the subsystem temperatures.

Housekeeping power while docked will be supplied directly to the regulators through the umbilical from one of the Airlock Module buses. The communication subsystem and various heaters will be the only components requiring this housekeeping power continuously, however just before a mission all systems will be powered up using the power from the umbilical.

6.5 THERMAL CHARACTERISTICS

The batteries, with heaters, can be operated within a temperature range of -65°F to 165°F. However for optimum performance they should be maintained between +50°F and 135°F. These optimum limits may be difficult to maintain, however attempts should be made to keep temperatures as close to this range as possible to insure high cycle life. The batteries themselves will generate 57 watts of heat total during discharge, but negligible heat during charge or trickle charge. If the 57 watts is entirely contained in the batteries, it will raise the temperature at a rate of only .65°F per hour.

Regulators will have a temperature range greater than the batteries, so if they are located near the batteries they will not exceed their limits. These regulators will dissipate about 8 watts of heat during discharge. The inverters and wiring will also dissipate about 13 watts.

6.6 RELIABILITY

A percentage figure for power system reliability can only be obtained through a testing program which will be done before the Teleoperator can fly. However, system reliability will be high because of the use of redundant equipment in the system for all active components and because all components are space proven. Even with failure of a regulator and/or inverter, the Teleoperator can be operated at 100% capacity. Battery failure will not cause mission failure but will lower maximum mission time by no more than 5 hours. Actual tests on 70. A-hr cells performed by the manufacturer show that at discharge rates near C/10 a 70 A-hr cell actually has 80.0A-hrs capacity, and thus there is ample leeway for completing 80% of a mission (8 hrs) using 75% of this larger capacity. Such failures as these however, will certainly be very improbable.

REFERENCES

1. Bauer, Paul, Batteries for Space Power Systems, NASA Report SP-172, 1968.
2. Pro, Stanley, "Power Conditioning for Satellite Systems", NASA Report TR-1001(2307)-6, March 1967.
3. Francis, Howard T., Space Batteries Technology Handbook, NASA Report SP-5004, 1964.
4. Gibson, Richard, "Design Data for Space Power Systems" The Bendix Corporation, Aerospace Systems Division, Feb. 1970.
5. Corliss, William R., Scientific Satellites, NASA Report SP-133, 1967.
6. DC Power Supply Handbook, Hewlett Packard, Harrison Division, 1967.
7. Yardney Silicad Batteries, Yardney Electric Co., 1968.

7
THERMAL CONTROL

7.1 INTRODUCTION

In order to operate in an efficient manner, the components of the various subsystems of our Teleoperator must be kept within a specific temperature range. Keeping these components within their allowable temperature range is the task of the thermal subsystem.

For purposes of analysis, the thermal problem can be broken down into two cases:

1. Thermal control of the Teleoperator when it is operating (powered up). In this case, the basic problem is eliminating the excess heat generated by the various subsystems.
2. Thermal control of the Teleoperator when it is docked with the Skylab (powered down). Here, heaters will be used to keep the Teleoperator within the allowable temperature range.

Table 7.1 shows the thermal requirements which have been placed on REMUS.

Table 7.1 Thermal Requirements

Subsystem	Optimum Temp. Range (F)
Attitude & Control	-15 to 125**
Power	0 to 125
Communications	0 to 150
Video	-22 to 185
Manipulators	0 to 130

** Attitude & Control has an internal gyro system which must be kept at 180 F $\pm$ 1 F.

7.2 SYSTEM DESCRIPTION

In the most basic sense, REMUS's steady-state thermal control system is based on the heat balance quation

$$Q_{in} = Q_{out}$$

This equation implies that all of the heat which enters REMUS must be accounted for.

For the powered up mode, passive thermal control can be used to provide an acceptable working temperature. For the powered down mode, however, it will be necessary to use semi-passive measures to control the temperature. These semi-passive measures will include heaters and an umbilical cord from Skylab to supply the power to the heaters.

Since aluminum is an excellent conductor of heat, the surface area of the Teleoperator can be used as a heat sink to radiate the heat to space. The base frame of the Teleoperator is also made out of aluminum and is reinforced with struts in a number of places. These struts will be used as heat paths to transfer the heat from the internal components to the surface of the Teleoperator.

Table 7.2 contains the approximate amount of heat that will be generated by each subsystem.

Table 7.2
Internal Heat Generated

Subsystem	Heat (watts)
Attitude & Control	50
Power	75
Communications	35
Video	100
Manipulators	50 (ave)
Total	310 watts

Besides internal heat generated by each subsystem, heat for the Teleoperator comes from three other places (see Figure 7.1):

1. heat from the sun = Q_{sun}
2. sunlight reflected from the earth = Q_{ref}
3. infrared radiation from the earth = Q_{ir}

The Steffan-Boltzman equation for a flat plate can be modified and used as a reasonably accurate method of finding out the maximum and minimum steady state temperatures of the external thermal control surfaces. This equation and its solution in a number of interesting cases can be found in Appendix F.

7.3 THERMAL COMPONENTS

7.3.1 Thermal Control Coatings

Thermal coatings are a passive means of regulating the temperature of a surface by selectively controlling the amount of solar energy absorbed and the amount of infrared energy emitted. For our purposes we will require two different types of thermal coatings.

It is desirable to keep the gaseous nitrogen propellant stored in a cylinder on top of the Teleoperator at a low temperature. This is to prevent the pressure inside from becoming so high that the tank would rupture. Therefore, its radiating surface will be coated with S-13G, a dull white organic paint (α = .2, ϵ = .9), to minimize the amount of solar energy absorbed and maximize the amount of heat radiated away.

For the rest of the Teleoperator, it was necessary to make a trade-off to decide on the type of paint to be used. When the Teleoperator is powered up, a large amount of heat is generated and it would be desirable to have a thermal coating with a low absorptance so as to minimize the amount of heat absorbed. However, when the Teleoperator is in the powered down mode, it is desirable to have a large amount of heat absorbed so as to minimize the power requirements for the heaters.

A paint formulated with α = .4 and ϵ = .9 was found to satisfy both requirements and provide the necessary thermal control.

7.3.2 Insulation

In a number of places in the Teleoperator, it is desirable to minimize the amount of heat transfer for various reasons. Insulation is used for this purpose. The insulation used will be Al/$\frac{1}{4}$ mil Mylar at approximately sixty layers per inch.

Insulation will be used in the following areas:

1. Approximately 1/2 to 3/4 inch of insulation will be used to completely encircle the cold gas reservoir on top of the Teleoperator. This will allow little heat transfer from the Teleoperator and, since we are using a thermal coating with low absorbtivity on the cylinder, it will keep the gas at a sufficiently low temperature.

2. At least one inch of insulation will be used to surround about 95% of the gyro package in the attitude and control subsystem. This package must be kept consistently at 180°F and, so as to conserve power by not having to run the heaters, constantly insulation will be used to keep heat transfer from the gyro as low as possible.

7.3.3 Heaters

When the Teleoperator is in its powered down mode, it will require heating to keep it at a reasonable temperature. The heater power will be supplied from Skylab through an umbilical cord. The heaters that will be are made by Electorfilm Corporation and are strip type heaters. They are space qualified and are "off-the-shelf" items. The power output of these heaters will be 10 watts per square inch. Simply by varying the size of the heater, the desired power output can be obtained.

In Appendix F, the amount of heating required to keep the cameras, the manipulator arms, and the flatbed base at 80°F is solved for. At no time will we attempt to keep the powered down Teleoperator at 80°F. A more reasonable temperature would be 20°F. However, the extra heaters will be included in the Teleoperator as a safety factor in case of the failure of some of the heaters. Table 7.3 lists the size of the heaters for each subsection.

The thickness of these heaters is approximately .0001 inch so they can be located almost anywhere in the Teleoperator.

Table 7.3
Location of Heaters

Subsystem	Heater Power	Total Power
Camera 1	39 watts	39 watts
Camera 2	39 watts	39 watts
Camera 3	39 watts	39 watts
Left manipulator arm	13 watts/motor	91 watts
Right manipulator arm	13 watts/motor	91 watts
Flatbed base	110 watts	110 watts
Total		409 watts

7.3.4 Thermocouples and Thermal Switches

In a number of pertinent locations around the Teleoperator, the temperature will be measured by means of a thermocouple and the information will be telemetered back to the control board on Skylab. Thermal switches (and one level of backups) will be located on the Teleoperator to turn the heaters on and off. When the Teleoperator is in its powered down mode, the on-board computer on Skylab will monitor the temperatures in various parts of the Teleoperator. When a part reaches 15°F, the switch will be activated and the part will be heated until it reaches, say, 30°F. Then, the part will be allowed to cool until it reaches 15°F again, and the process will begin again.

Seven thermal switches will be used so that different parts of the Teleoperator can be heated or not heated as required. The thermal switches control the heaters in the following specific parts of the Teleoperator: One switch for each manipulator arm, one switch for each camera, one switch for the gyro package, one switch for the base frame for a total of seven switches.

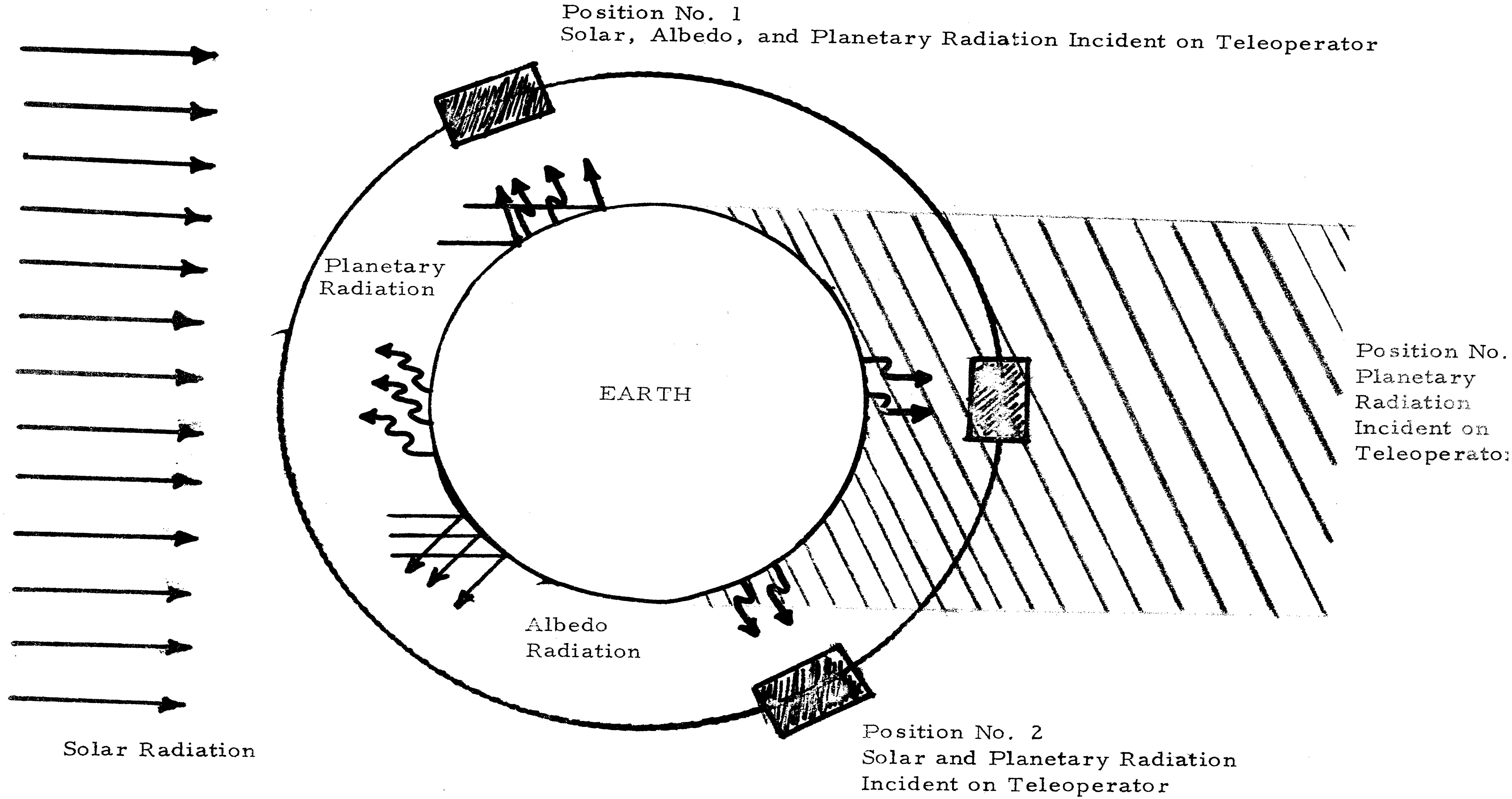


Figure 7.1 Diagram of Radiation Incident on the Teleoperator at Different Positions in Its Orbit (Three Different Combinations of Radiation Occur

The thermocouples will be located in the following places: Two for each camera, two for the nitrogen tank, two for the gyro package, and four for the base frame for a total of 14 thermocouples.

7.4 WEIGHT OF THERMAL SUBSYSTEM

Component	Weight (lb)
Thermocouples and associated wiring	1
Heaters and associated wiring	2
Insulation	2
Switches	1
Total	6 lbs max. wt.

7.5 SKYLAB MODIFICATIONS

Only a minimal number of modifications will have to be made in the Skylab in order to interface with the thermal control section of the Teleoperator. On the display panel, fourteen dials and idiot lights to read the temperatures in the Teleoperator will have to be set up. In addition, seven switches will have to be included in order to manually override the automatic controls.

Included in Skylab will be a monitoring system to automatically start the heaters when the temperature in the various parts of the Teleoperator falls below a programmed temperature (e.g. $15^{o}F$). The on-board computer can be used to check for this and to issue the command to start the heaters.

REFERENCES

1. Kreith, Frank, Radiation Heat Transfer for Spacecraft and Solar Power Plant Design, Scranton, Pa., International Textbook Company, 1962.
2. Mason, Dr. J. L., Vehicle Energy Balance, University of California at Los Angeles Textbook, September 1961.
3. Van Vliet, Robert M., Passive Temperature Control in the Space Environement, New York, The Macmillan Company, 1965.
4. Project Observer, University of Michigan Design Project, December 1968.
5. Project Scannar, University of Michigan Design Project, April 1970.
6. Thermal Insulation Systems, A Survey, NASA Report No. SP-5027, November 1967.

8
STRUCTURES

8.1 INTRODUCTION

The Teleoperator structural configuration was designed to accommodate all the requirements and limitations resulting from the mission analysis. Of prime consideration was the support and protection of subsystem components in prelaunch, launch, and orbital environments.

The basic structure of the Teleoperator consists of a payload flat-bed on top strengthened by square section extruded aluminum tubing attached to peripheral skins. This style of construction has been chosen for several reasons:

1. Rather than uniformly distributed loads, almost all of the loads imposed by the Teleoperator's subsystems on the base structure are concentrated loads that require localized support structure. For example, there are the concentrated loads at the manipulator arm mounting fittings, docking tether motor fittings, camera platform mounting fitting, and various subsystem mounts.

2. The ribs provide many versatile mounting surfaces for new equipment, additional equipment, and equipment shifted to control the overall center of mass.

3. The ribbed construction facilitates the addition of equipment access doors.

4. The ribbed construction transfers the launch loads between the base substructure frame and all the Teleoperator subsystems.

5. The ribbed construction stiffens the vehicle both flexurally and torsionally without requiring structural doors or thick skins on the lower and side surfaces of the base.

Equipment was placed so that the center of mass and principal axes would lie near the center of the base substructure and thus allow optimum thruster placement. Special consideration was given to the placement of the two omni antennas and sun sensors to provide them with unobstructed "windows." Because of the problem of glare, anodized aluminum was used for the upper surface of the payload flat-bed in view of the central mounted cameras. The need for reliability dictated that a minimum of moving parts be used and that all mechanical system be as simple as possible. Overall constraints of light weight and ease of fabrication also had to be considered.

Aluminum alloys were chosen for structural members because of their low weight and high strength. Aluminum honeycomb was used for the payload flat-bed for similar reasons. Mechanical fittings and connections were used throughout to allow easy access to the Teleoperator interior prior to launch and to avoid the difficulties of welding heat treated aluminum alloys.

The launch subjects the Teleoperator to its severest loadings and thus sizes its structural members. It further specifies that all members of the Teleoperator have fundamental frequencies higher than 20 cps axially and 25 cps laterally. Because of the way the Teleoperator is positioned during launch, the center of mass was kept as close to the base substructure bottom frame as possible, thus preventing unusually large bending moments on the launch securing system.

The structural components are described separately in Sections 8.2-8.12; their locations are shown in Figures 8.5, 8.8, 8.10, and 8.12. The launch securing structural components are shown in Figures 8.1 and 8.4.

8.2 BASE SUBSTRUCTURE FRAME (BOTTOM)

The bottom frame of the base substructure is the main structural member of the Teleoperator. It is the primary means by which loads are transferred from the Teleoperator components to the aluminum launch baseplate and subsequently to the ATM trusses on Skylab with which it is launched. The majority of the internal subsystem components are attached directly to the extruded aluminum square section ribs of which it is constructed. The tubular ribs have 3" facings, are 0.249" thick, and consist of 7075-T6 aluminum. The ribs are arranged in the basic ellipse shape of the substructure base with the base cross members strengthening them both horizontally and diagonally. External subsystem loads are transferred to the base substructure bottom frame through the vertical support ribs and manipulator arm supports. The frame is 46" long and 37" wide and the various ribs comprising it are joined using L-clamps and then bolted. The internal components are connected to the frame by bolting them directly to the ribs or using C-clamp fittings.

8.3 BASE CROSS MEMBERS

The base cross members strengthen the base substructure bottom frame and base substructure top frame both flexurally and torsionally. They provide a path to transfer loads from the external subsystems (top frame) and internal components (bottom frame) to the base substructure frame during launch. There are four cross members for each of the two substructure frames with the top cross members consisting of extruded 7075-T6 aluminum square tubing 0.20 inches thick and having 2 inch facings, and the bottom cross members also of extruded 7075-T6 aluminum square tubing but 0.249 inches thick with 3 inch facings.

8.4 BASE COVERING

The base covering functions to strengthen the base substructure bottom frame and to protect the internal components. It is made of 2024-T86 aluminum sheet, 0.0625 inches thick, 37" wide and 46" long and is attached to the bottom frame with bolts.

8.5 VERTICAL SUPPORT RIBS AND VERTICAL CROSS MEMBERS

The nine vertical support ribs transfer the loads of the upper substructure frame and external subsystems to the base substructure bottom frame. They act as mountings for the thruster assemblies, the tethered television camera cradle, the docking tether motor attachment plates, and various internal components.

The six vertical cross members function to strengthen the vertical support ribs both flexurally and torsionally and are curved to give the substructure frame its elliptic shape. The vertical support ribs and vertical cross members are joined together and to the substructure bottom and top bases with L-clamps and bolts. Both the vertical support ribs and the vertical cross members are constructed from 7075-T6 aluminum extruded square tubing with 2 inch facings and 0.20 inches thick.

8.6 BASE SUBSTRUCTURE FRAME (TOP)

The base substructure top frame completes the box-like ribbed construction of the base substructure. The final closed nature of the base structure protects the internal subsystems both thermally and mechanically. The top frame is assembled in an identical manner to that of the bottom frame assembly, except that 0.20 inches thick 7075-T6 extruded aluminum square tubing is used for the framing and cross members.

8.7 SIDE AND FRONTAL COVERINGS

The side and frontal covering gives additional support to the vertical load carrying members of the base substructure as well as protection of the internal subsystems. The covering is made from 2024-T86 aluminum sheet, 0.0625 inches thick, 20 inches wide and in sections 12 inches long. These panels are bolted to the base substructure and thus allow easy access to the internal components both during prelaunch and in the orbital environment.

8.8 MANIPULATOR ARM SUPPORTS AND CROSS MEMBERS

The two manipulator arm supports transfer the loads of the manipulator arms and camera platform to the base substructure bottom frame both during launch and in orbital environment task situations. The manipulator arm support cross members offer additional strength and the top cross member serves as a mounting surface for the camera platform. The arm supports and cross members are joined together and to the frame structure with L-clamps and bolts in the manner of the substructure frame construction. They are made of 0.20 inches thick extruded aluminum square tubing with 2 inch facings.

8.9 PAYLOAD FLAT-BED

The payload flat-bed is the upper surface of the base substructure and is attached to the substructure with L-shaped mounting brackets and bolts. The camera platform and manipulator arm shoulder members are attached to the payload flat-bed with 2014-T6 aluminum flanges, 8 inches in diameter and 1 inch thick and bolted. In addition, the camera platform and manipulator arm shoulder members continue through the payload flat-bed and are joined to the manipulator arm supports and top manipulator arm support cross member with L-clamps and bolts. Beside these three 5 inch diameter holes the payload flat-bed has two holes each 2.5 inches in diameter to allow for thrusters4 and 9 (see Figure 4.1) and a fitting for the umbilical attachment. Further, the payload flat-bed acts as the mounting surface for the ATM film trees and cold gas storage tank. The storage tank is mounted to the payload flat-bed via a saddle machined from 2014-T6 aluminum, 10 inches long, 4 inches wide, and attached to the flat-bed with bolts from the underside.

The payload flat-bed is made of 0.75 inch honeycomb with 0.020 inch facings. The top facing is anodized to reduce the glare transmitted to the television cameras. It overhangs 5.5 inches on each side of the substructure to act as a "bumper" and protect the thruster assemblies. At the ends of the platform the facings are closed using a strip of perforated fiberglass. This resilient material will protect both Teleoperator and Skylab components in the event of a collision.

8.10 THRUSTER ASSEMBLY MOUNTS

Each thruster assembly consists of two groups of four thrustersjoined by a 7 inch length of 0.20 inch thick extruded 7075-T6 aluminum square tubing with 2 inch facings and fastened with L-clamps and bolts. This joining member is in turn bolted to the central vertical support rib on each side.

8.11 DOCKING TETHER MOTOR ATTACHMENT PLATES

The docking tether motor attachment plates transfer the loads from the docking tether units to the vertical support ribs and subsequently to the substructure base frame. They are 0.5 inches thick 7075-T6 aluminum plate fitted into the special cutouts in the forward vertical support ribs and bolted.

8.12 LAUNCH MOUNTING

It is proposed that the Teleoperator be launched in the ATM trusses with Skylab. This imposes two design constraints: First, the Saturn V launch will subject the Teleoperator to loads up to 8 G's. Secondly, once on station the Teleoperator must be able to remove itself from its launch mount.

The design chosen satisfies these constraints. The Teleoperator will be mounted with the payload flat-bed parallel to the plane of the ATM trusses in the region of the EVA Bay (see Figures 8.2 and 8.3). The launch mounting structural members are described in Sections 8.12.1 - 8.12.4.

8.12.1 Aluminum Base Plate

The aluminum base plate is the load transferring member between the Teleoperator base substructure bottom frame and the ATM trusses. It is made of 1 inch thick 7075-T6 aluminum plate and is attached to the ATM trusses with 6 structural steel C-clamps and bolted, thus avoiding any changes in the ATM truss members. Because the trusses narrow in the direction of the launch loads, this will be a self-securing launch mount. The middle section of the plate is cut out as shown in Figure 8.4 to allow for the omni antenna mounted on the underside of the Teleoperator.

8.12.2 C-Slip Joint and Aft Launch Securing Members

The C-slip joint and aft launch securing members are machined from 7075-T6 aluminum. They are shown in their launch configuration in Figure 8.4. The C-slip joint is joined to the aluminum base plate by bolts from the underside. The aft launch securing members fit into cut outs in the aft substructure frame and are joined with two 301 stainless steel pins and bolted.

8.12.3 Forward Launch Securing Members and Launch Bolts

The forward launch securing members and launch bolts secure the front portion of the Teleoperator during launch. The forward launch securing members are made from 7075-T6 aluminum plate, 1 inch thick, 5 inches wide, and 11 inches long. They fit into cut outs in the forward substructure bottom frame member, are pinned with two 301 stainless steel pins, and bolted. The launch bolts are made of 301 stainless steel and are tightened with a torque wrench to no more than 6 ft-lbs so that they can be removed by the manipulator arms once on station.

8.12.4 Securing Pins and Securing Plates

The securing pins and securing plates prevent lateral translation of the Teleoperator base during the launch phase. The plates are 5 inches x 5 inches x 1 inch and are made of 7075-T6 aluminum. They have a 1.5" cut out to allow the securing pins to slip out once on station. The securing pins are also of 7075-T6 aluminum. They are 1.5 inches in diameter, 10 inches long, and protrude from the substructure frame 4 inches. They are pinned and bolted to the forward bottom base cross member.

The forward launch securing members, aft launch securing members, and security pins are the main bearing points for arranging prelaunch transportation.

8.13 ON STATION RELEASE FROM LAUNCH CONSTRAINTS

Once on station, the Teleoperator can release itself from the launch constraints by following the procedure outlined below (illustrated schematically in Figure 8.1).

A. Remove umbilical
B. Remove launch bolts with manipulator arms

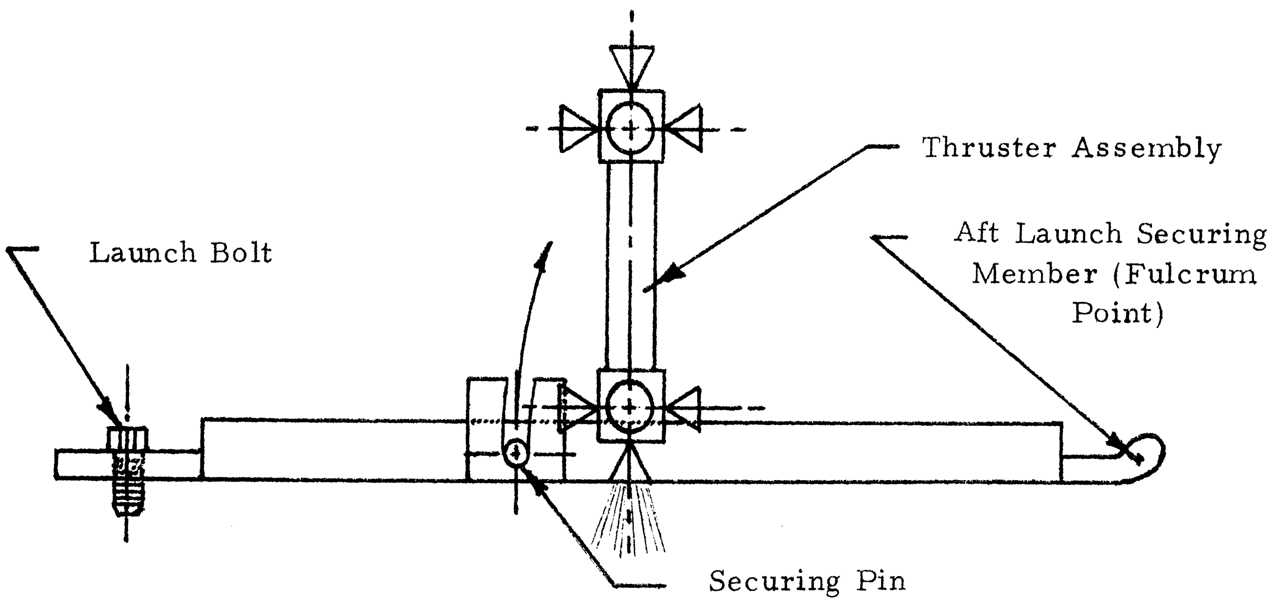


Figure 8.1 Schematic-On Station Release from Launch Constraints

C. Apply "up" thruster pulse
D. Apply "forward" thruster pulse

8.14 UMBILICAL ATTACHMENT

The umbilical will be of a coaxial nature with cold gas being transferred through the central tubing and electrical and communication lines on the outside. The Teleoperator will be launched with the umbilical attached. It will be removable and attachable with the manipulator arms. The connection will be of the "quick disconnect" variety already in use but will have an elliptical shape to ensure proper terminal hook-ups when reattached.

8.15 STRAIN GAGE "FEEL" SYSTEM (TELEMETRY)

To protect itself and Skylab components the Teleoperator will have 36 strain gages attached to the frame (distributed as follows: 18 around payload flat-bed periphery, 4 on base structure, 5 on portside, 5 on starboard side, 1 on each aft launch securing member, 1 on the upper omni antenna mount, and one on the lower omni antenna mount) to detect collisions. The power required to run the strain gages (20 milliamps) is negligible. The strain gage signals go into a differential amplifier and are processed by communications.

8.16 PARTS SPECIFICATION

Item	Number	Total Weight lbs	Material
Base Substructure Frame (Bottom)	1	13.4	7075-T6 square aluminum tube 0.249" thick 3" facings
Bottom Base Cross Members	4	16.2	7075-T6 square aluminum tube 0.249" thick 3" facings
Base Substructure Frame (Top)	1	4.7	7075-T6 square aluminum tube 0.20" thick 2" facings
Top Base Cross Members	4	5.65	7075-T6 square aluminum tube 0.20" thick 2" facings
Base Covering	1	10.6	2024-T86 aluminum sheet 0.0625" thick
Vertical Support Ribs and Vertical Support Members	15	9.8	7075-T6 square aluminum tube 0.20" thick 2" facings

Side and Frontal Coverings	10	15.0	Panels 20" wide, 12" long, 0.0625" thick 2024-T86 aluminum sheet
Manipulator Arm Supports and Cross Members	4	1.92	7075-T6 square aluminum tube 0.20" thick 2" facing
Payload Flat-Bed	1	8.62	Honeycomb sandwich: core: 0.75" 5052-H39 aluminum 0.1875" hex cells 0.001" wall thickness facings 0.020" 7075-T6 aluminum top surface anodized
Camera Platform Flanges Manipulator Arm Flanges	3	3.1	2014-T6 aluminum 1" thick
Cold Gas Storage Saddle	1	3.5	2014-T6 aluminum
Thruster Assembly Mounts	2	.68	7075-T6 aluminum square tubing 0.20" thick, 2" facings
Docking Tether Motor Attachment Plates	3	2.7	7075-T6 aluminum plate 0.5" thick
Aft Launch Securing Members	2	10.5	7075-T6 aluminum
Forward Launch Securing Members	2	10.5	70751T6 aluminum plate 1.0" thick
Securing Pins	2	1.12	7075-T6 aluminum 1.5" dia.
Stainless Steel Pins, Bolts and Other Hardware		15.4	
Total Vehicle Structures Weight		133.39 lbs	

Launch System Weight

Aluminum Base Plate and C-Clamps and Bolts	1	109.6	7075-T6 aluminum plate 1.0" thick
C-Slip Joint	1	6.1	7075-T6 aluminum
Securing Plates	2	4.9	7075-T6 aluminum plate 1.0" thick
Total System Structures weight		120.6 lbs	
TOTAL SYSTEM STRUCTURAL WEIGHT		253.99 lbs	

Table 8.1 Moments of Inertia and Center of Mass Locations

Teleoperator Configuration	1	2	3	4	5	6
Distance to C. M. Measured Along Principal Axes	x = 0 y = 0 z = 0	x = +2.7'' y = 0 z = 0	x = +9.3'' y = 0 z = 0	x = +6.2'' y = 0 z = +2.1''	x = +1.8'' y = 0 z = +2.1''	x = -2.6'' y = 0 z = +2.1''
I_{zz} Slug-ft^2	52.5	62.0	111.2	114.5	65.3	55.9
I_{yy} Slug-ft^2	48.6	59.3	111.7	119.9	67.5	56.8
I_{xx} Slug-ft^2	41.2	41.2	44.2	51.5	48.4	48.4

Axis Notation as in Figure 4.1.

Condition 1: Arms folded, tethers in, no payload
Condition 2: Arms folded, tethers extended 4 ft, no payload
Condition 3: Arms maximum extended, tethers extended 4 ft, no payload
Condition 4: Arms maximum extended, tethers extended 4 ft, maximum payload (114 lbs)
Condition 5: Arms folded, tethers extended 4 ft, maximum payload (114 lbs)
Condition 6: Arms folded, tethers in, maximum payload (114 lbs)

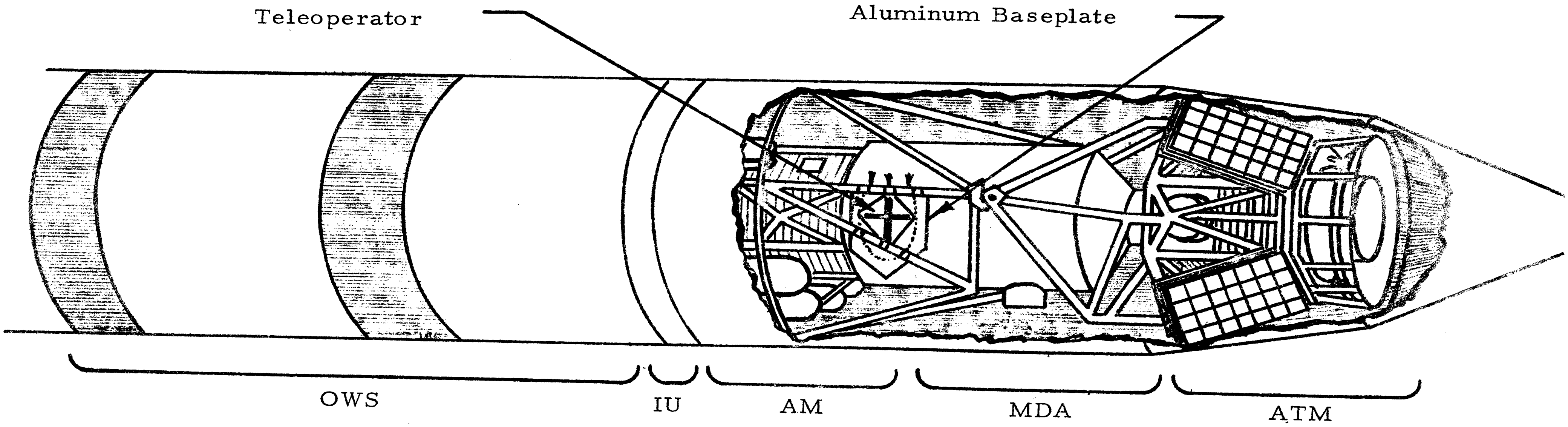


Figure 8.2 Skylab Launch Configuration Showing Teleoperator in Its Launch Configuration.

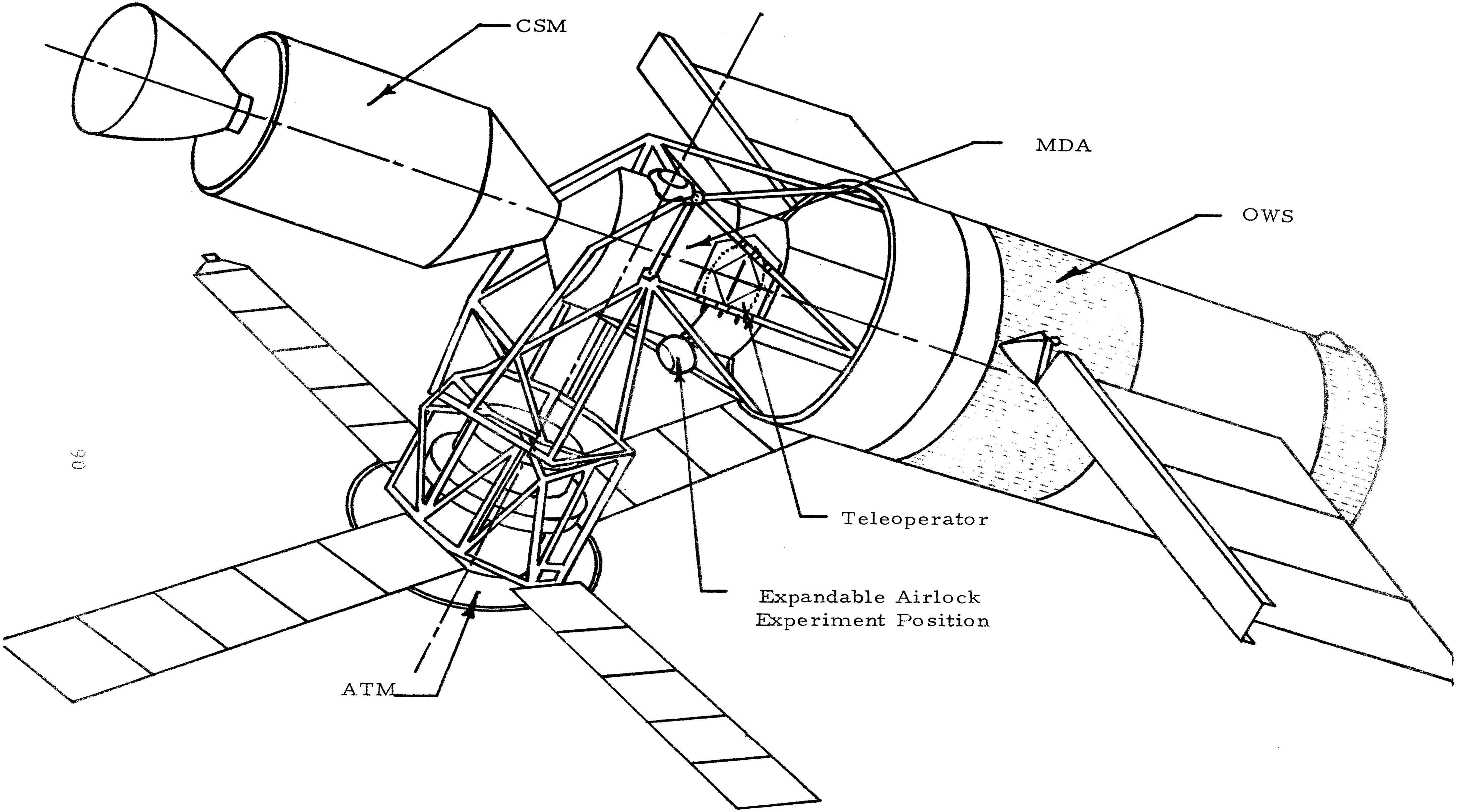


Figure 8.3 Skylab Deployed Configuration Showing Teleoperator in its Launch Configuration

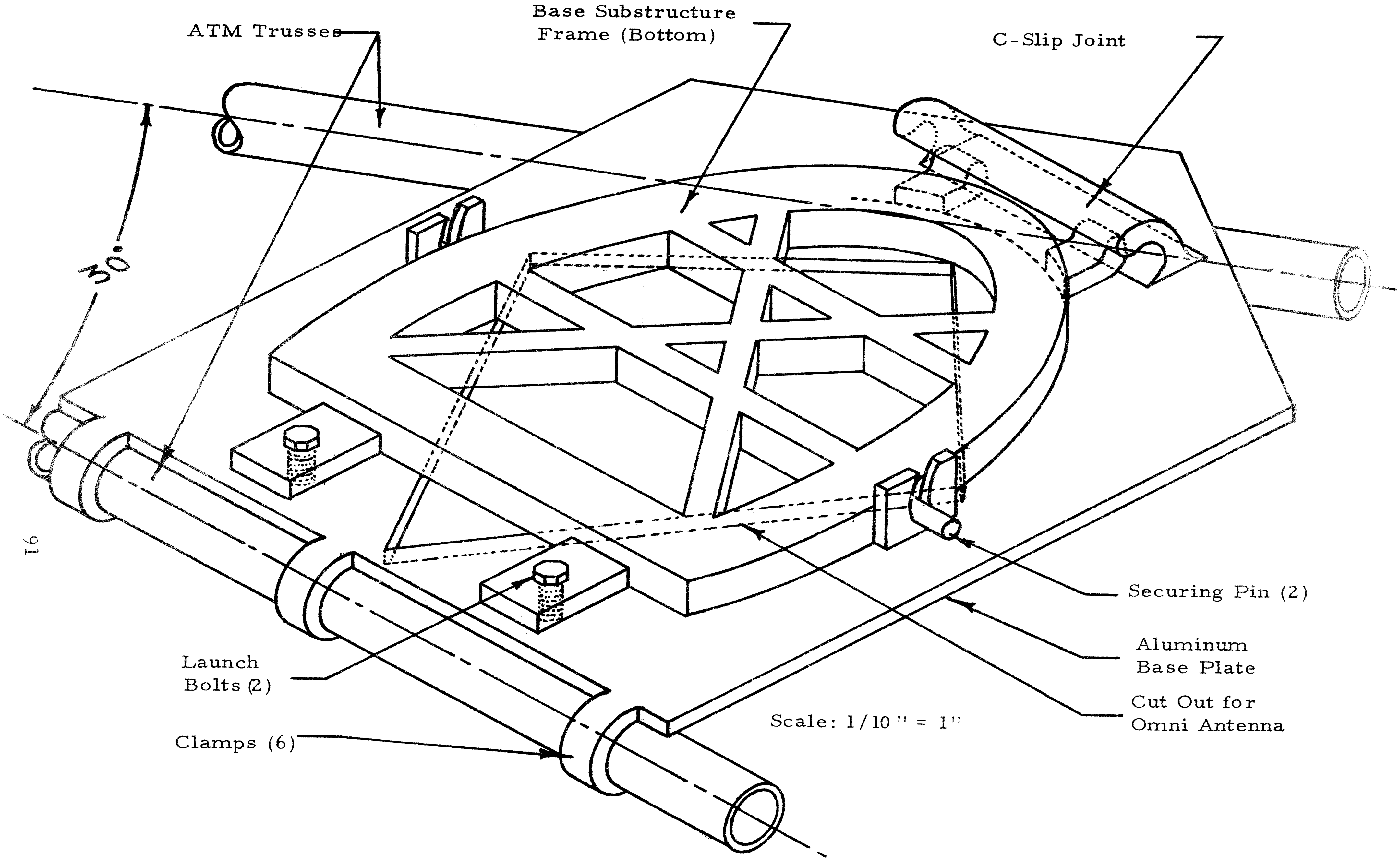


Figure 8.4 Launch Structure Isometric View

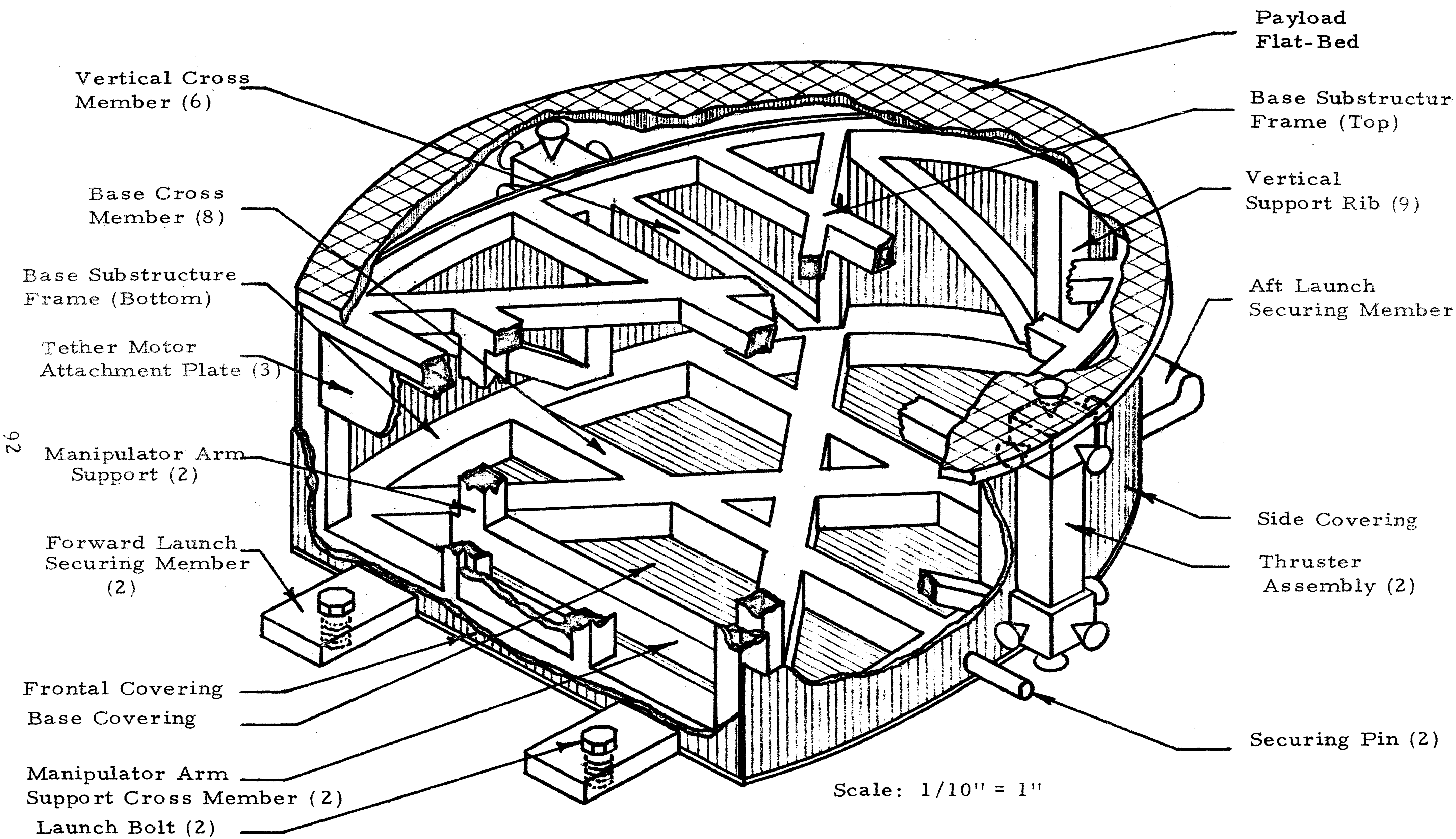
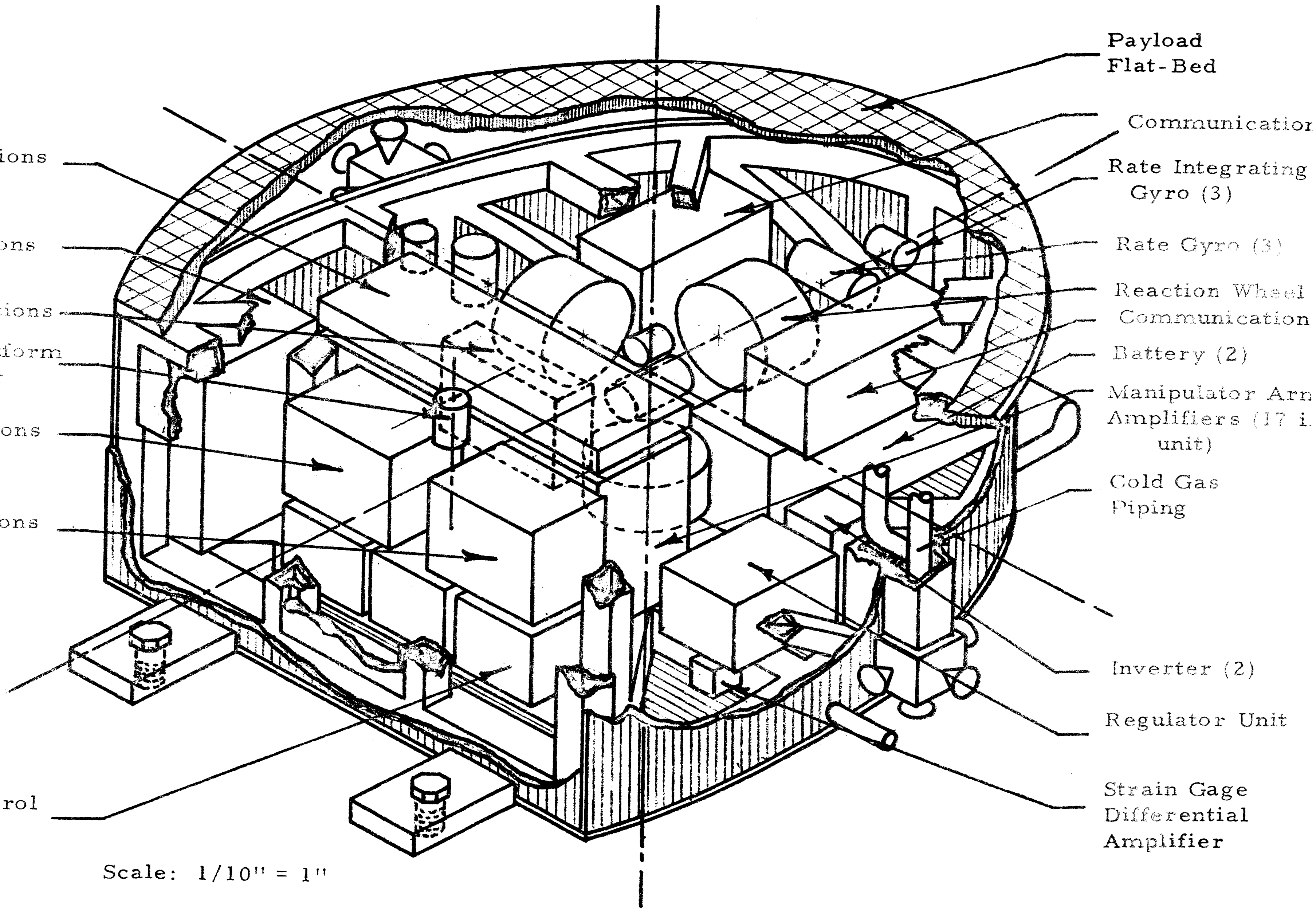
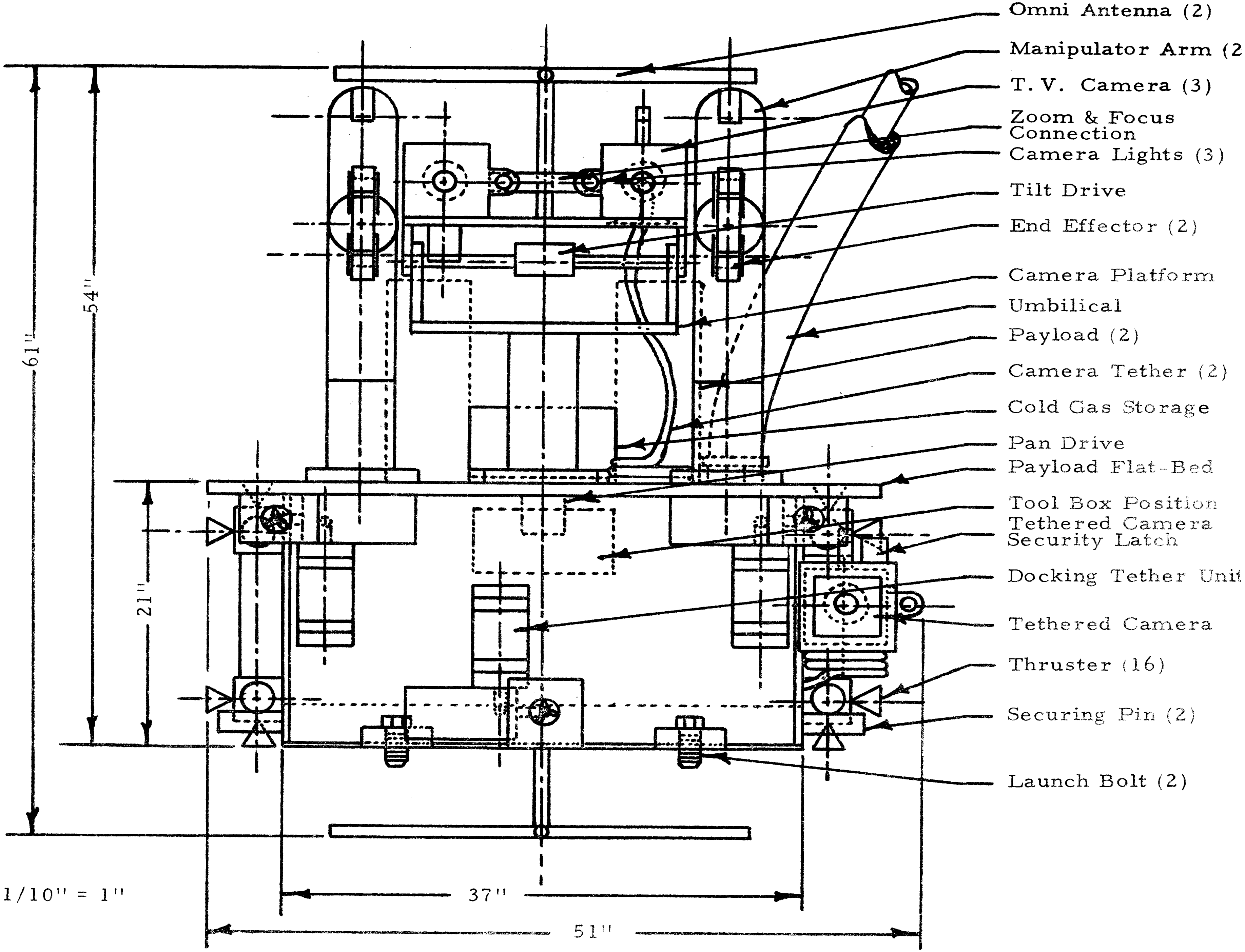


Figure 8.5 Structural Components - Isometric View



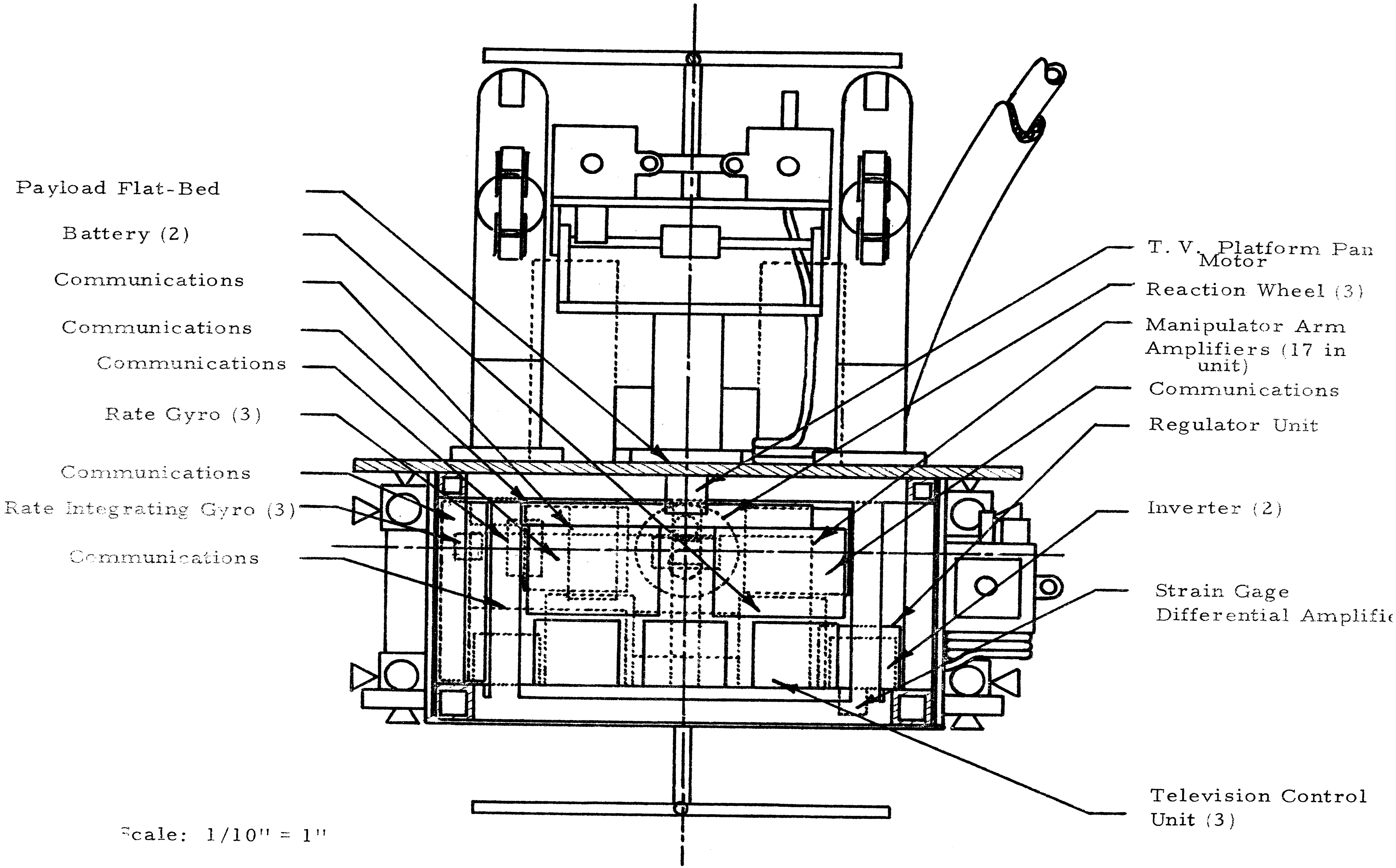
Scale: 1/10" = 1"

Figure 8.6 Internal Components - Isometric View



Scale: 1/10" = 1"

Figure 8.7 Front View-Exterior



Scale: 1/10" = 1"

Figure 8.8 Front View - Internal Cutaway

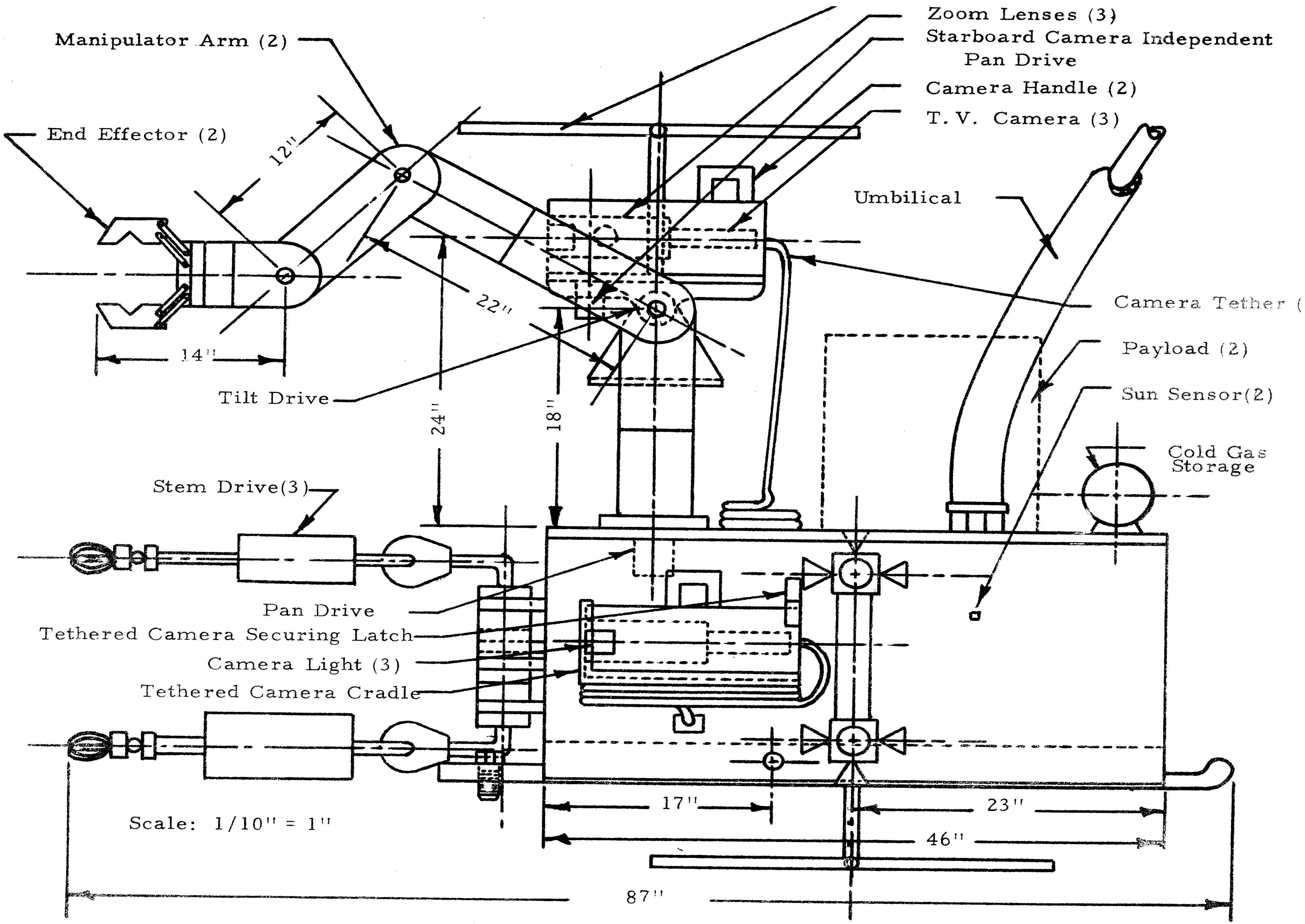
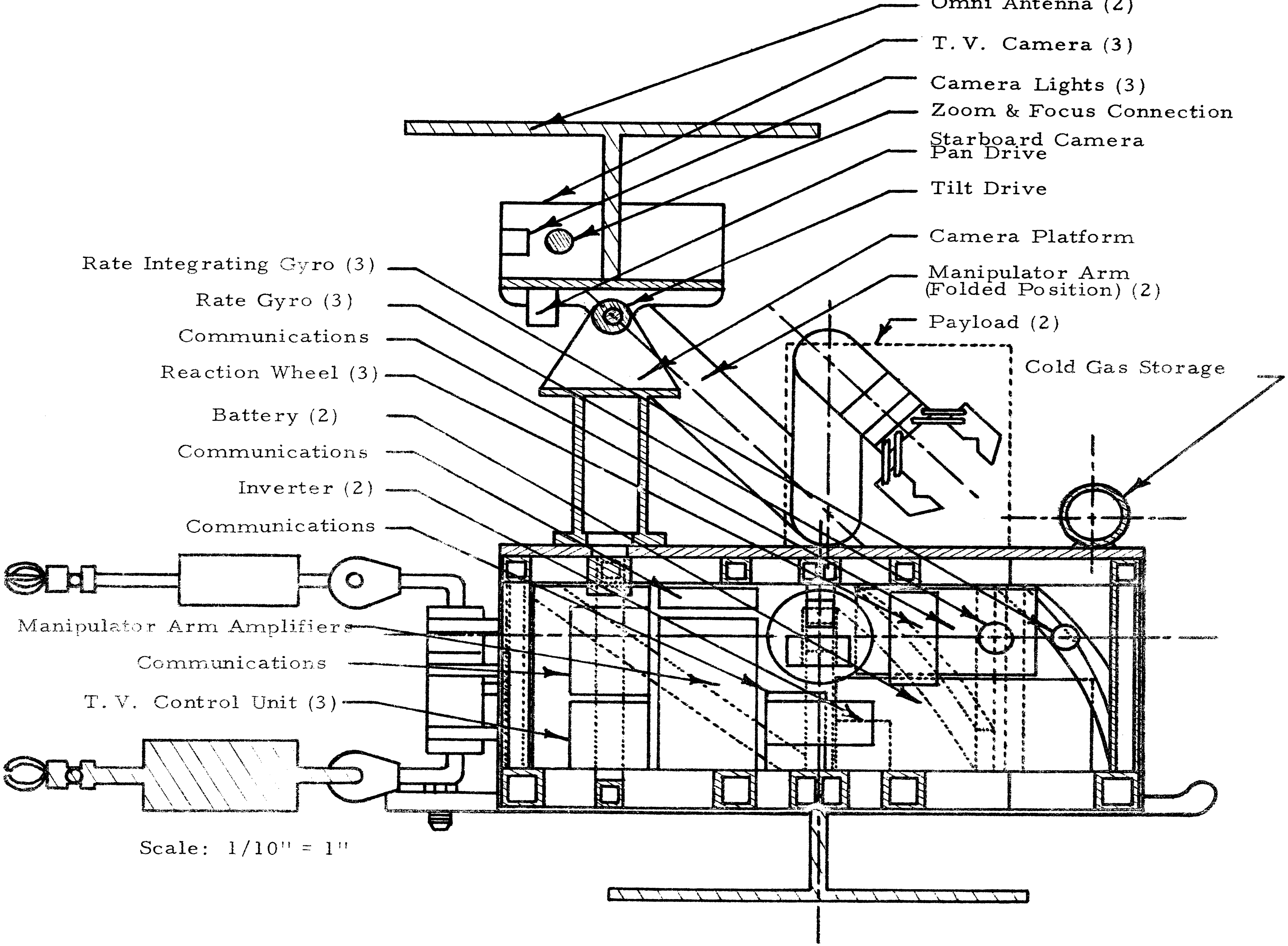


Figure 8.9 Side View Exterior



Scale: 1/10" = 1"

Figure 8.10 Side View - XZ Plane Internal Cutaway

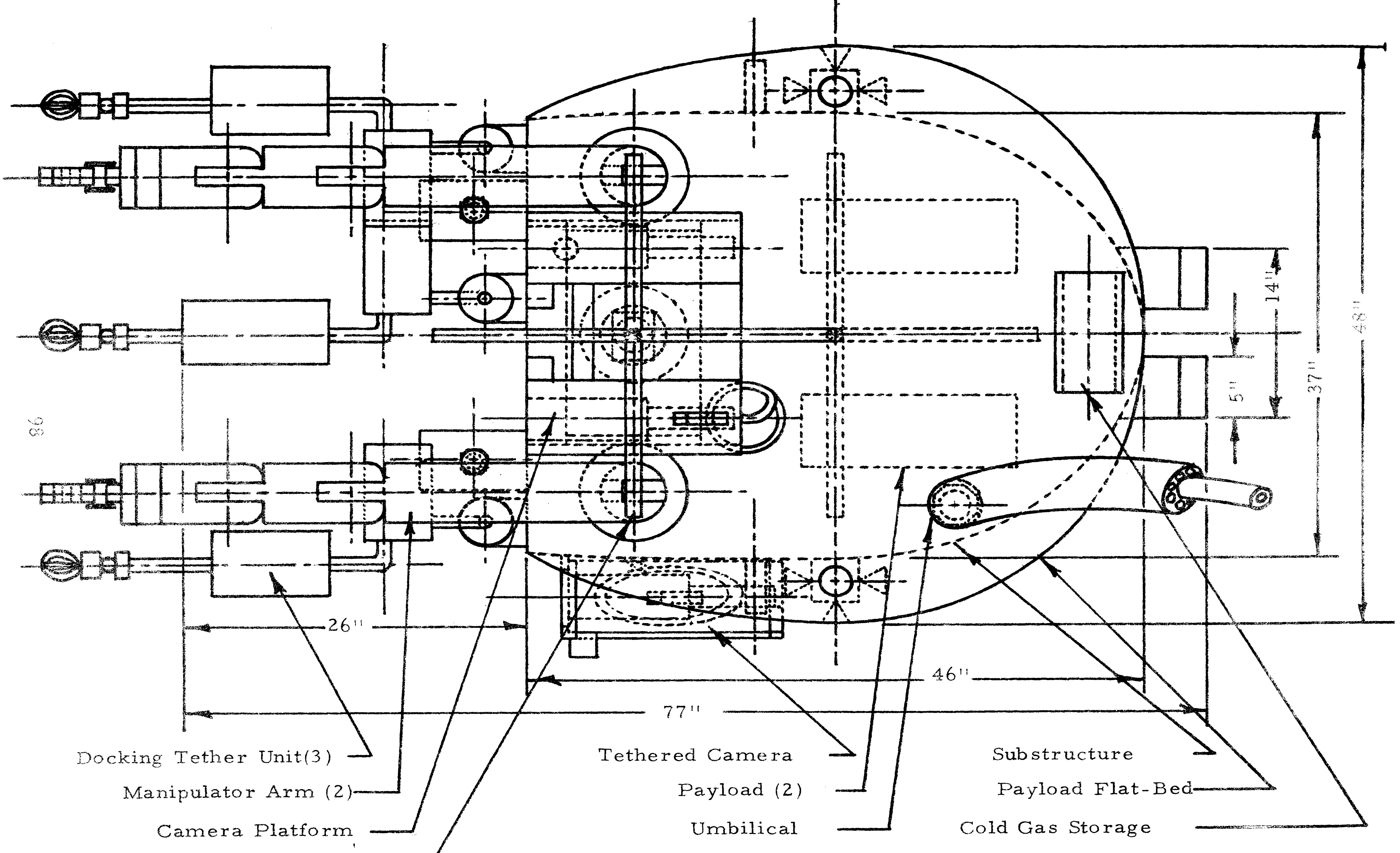
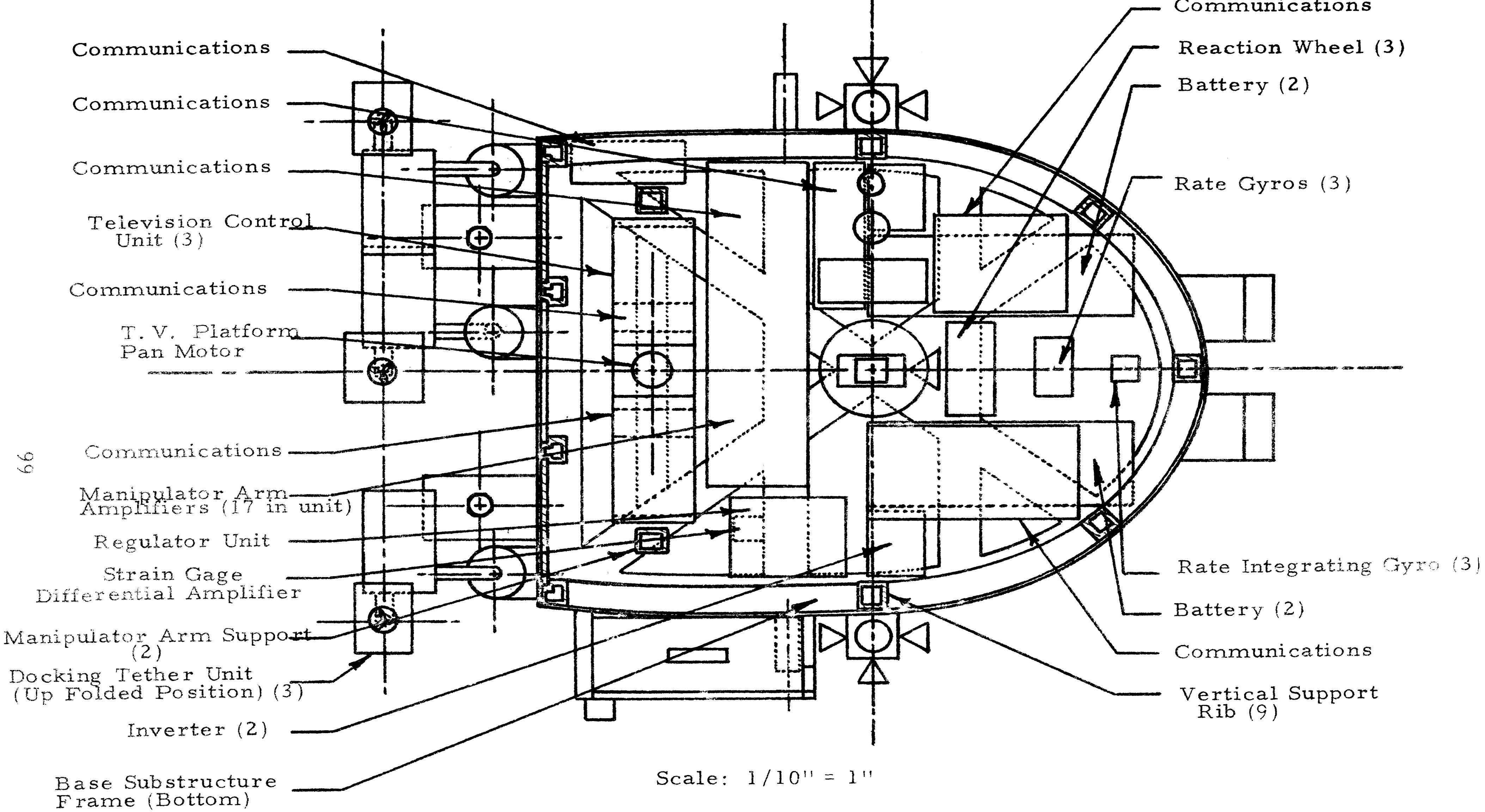


Figure 8.11 Top View Exterior



Scale: 1/10" = 1"

Figure 8.12 Top View - Internal Cutaway

8.17 EQUIPMENT PLACEMENT

Once all Teleoperator components were identified they had to be assembled and placed to keep the center of mass near the geometric center of the base substructure, thus assuring that the principal axes would lie well within the structure for proper attitude and control. Components were so located about the XZ and YZ planes (see Figure 4.1) as to cancel out all products of inertia. Tradeoffs between the various subsystem demands resulted in the final Teleoperator configuration.

Table 8.1 shows moments of inertia and center of mass locations for various Teleoperator configurations. Figure 8.1 is a schematic of the on station release from the launch constraints. Figures 8.2 and 8.3 show the Teleoperator launch configuration in the ATM trusses of Skylab. Figure 8.4 is an isometric view of the launch constraint structure. Figure 8.5 is an isometric view of the structural components. Figure 8.6 is an interior isometric cutaway view of the internal subsystems. Figures 8.7, 8.9, and 8.11 show the exterior components of the Teleoperator and Figures 8.8, 8.10 and 8.12 show the location of the internal subsystems.

REFERENCES

1. Crandall and Dahl, Introduction to the Mechanics of Solids, New York, McGraw-Hill, 1959.
2. Timoshenko and Gere, Theory of Elastic Stability, New York, McGraw-Hill 1966.
3. Shames, Engineering Mechanics, Vol. II, Dynamics, Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 1966.
4. SCANNAR, University of Michigan, Department of Aerospace Engineering Design Project, April 1970.
5. Osgood, Spacecraft Structures, Englewood Cliffs, New Jersey, Prentice-Hall, 1966.
6. Wolff, Spacecraft Technology, Washington, McGregor & Werner, Inc., 1962.
7. The Aluminum Data Book, Richmond, Reynolds Metals Company, 1958.
8. Koelle, Handbook of Astronautical Engineering, New York, McGraw-Hill, 1961.
9. Carrazzone & Interian "The Definition and Development of a Teleoperator Space Tug Experiment to be Conducted from a NASA Manned Space Station", Vol. II, General Electric Company, Valley Forge Space Center, Oct. 1969.

9
IMPLEMENTATION

9.1 INTRODUCTION

This section will complete the study of Project REMUS with a brief discussion of its implementation. The main topics covered are work scheduling, cost analysis, and test and reliability.

9.2 WORK SCHEDULING

A work schedule based on a launch date of Skylab (SIVB) in January of 1976 is shown in Table 9.1. The instrumentation to go on-board Skylab will be delivered in March of 1975 and two Teleoperators will be delivered October of 1975 to be ready for the January launch.

9.3 COST ANALYSIS

The total cost of Project REMUS is estimated at 22 million dollars. This includes the design, fabrication, and testing of a structural model, prototype, and a qualification test article. It also includes the cost to build, test, and deliver two flight accepted spacecraft and on-board instrumentation for Skylab (SIVB). The costs are broken down in Tables 9.2 and 9.3. Table 9.2 is divided according to material, labor, and other general expenditures. Table 9.3 splits the cost into recurring and nonrecurring cost. The non-recurring costs include those to design, develop, and qualify the spacecraft. The recurring cost includes the expenses to fabricate, test and deliver one flight unit.

Table 9.2
REMUS Cost Estimate

Direct Labor	
Engineering	$ 4,800,000
Other	3,000,000
Labor Burden (at 110%)	8,500,000
Direct Material	2,000,000
Travel	300,000
Other Direct Cost	100,000
	18,700,000
General & Administrative	2,000,000
Total Estimated Cost	20,700,000
Profit	1,300,000
Total Program Cost	$ 22,000,000

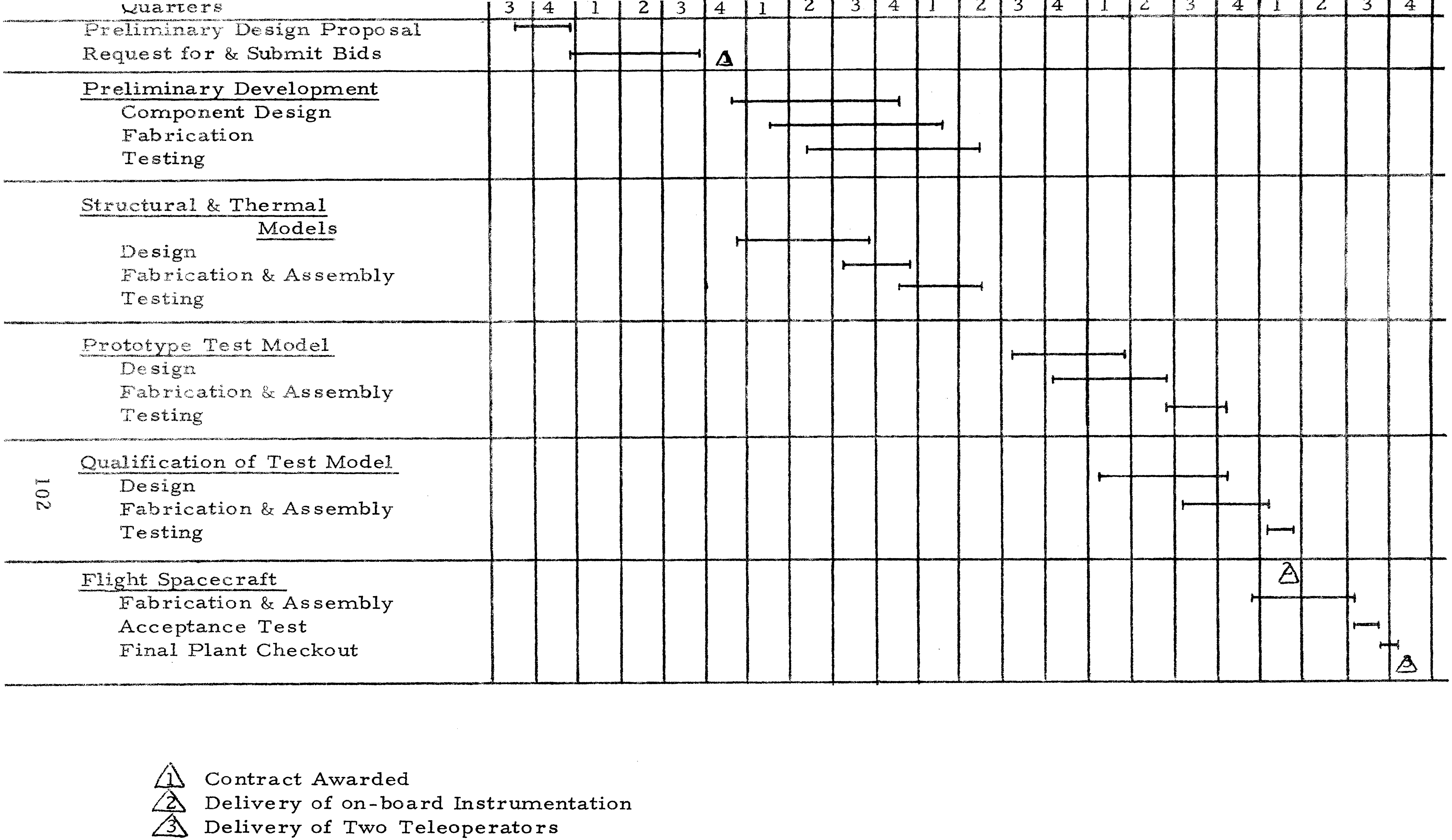

Quarters
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Preliminary Design Proposal
Request for & Submit Bids
Preliminary Development
Component Design
Fabrication
Testing
Structural & Thermal Models
Design
Fabrication & Assembly
Testing
Prototype Test Model
Design
Fabrication & Assembly
Testing
Qualification of Test Model
Design
Fabrication & Assembly
Testing
Flight Spacecraft
Fabrication & Assembly
Acceptance Test
Final Plant Checkout
1 Contract Awarded
2 Delivery of on-board Instrumentation
3 Delivery of Two Teleoperators

Figure 9.1

Table 9.3
Project REMUS Cost Breakdown

Non-recurring costs	
Development	$ 17,000,000
Qualification	2,000,000
Recurring costs	
1 Console & 2 Teleoperators	3,000,000
	$ 22,000,000

9.4 TESTING AND RELIABILITY

In order to insure a high degree of reliability, time must be spent in extensive testing. The testing sequence is briefly described below.

The first tests, Component and Assembly Development Tests, will be to check out the components of each subsystem. Next a structural thermal test article is fabricated and tested. All subsystems will be simulated as black boxes sufficient to duplicate the center of mass, weight and heat output. The test article will consist of the following:

1. Body structure
2. Thermal control
3. Fuel tanks
4. Subsystem simulators
5. Antennas
6. Instrumentation

The following tests will be performed on the model:

1. Vibration
2. Shock
3. Thermal vacuum with solar simulation.

Development testing is completed with the prototype. This test article will be a complete spacecraft with fully operational subsystems. In step nine below, the entire mission will be simulated in the space environment to see how the components react as a total system in simulated space. The following is a list of test to be completed on the prototype:

1. Ambient functional
2. Mass properties
3. Vibrational (stowed position)
4. Ambient functional
5. Shock (stowed position)

6. Ambient functional
7. Acceleration (stowed position)
8. Ambient functional
9. Mission simulation
10. Ambient functional

The qualification test article must now be tested in the space environment (Acceptance test) and also to the limits the spacecraft was designed (Design margin test). The following is a list of these tests:

Acceptance Test

1. Ambient functional
2. Mass properties
3. Vibration
4. Ambient functional
5. Acceptance thermal vacuum
6. Ambient functional

Design Limit Test

1. Vibration
2. Ambient functional
3. Shock
4. Ambient functional
5. Acceleration
6. Ambient functional
7. Design limit thermal vacuum
8. Ambient functional.

Before the flight models are delivered they undergo acceptance tests described above. When they arrive at the launch facilities they must go through a set of prelaunch tests which include the following:

1. Spacecraft inspection
2. Spacecraft acceptance test
3. Final checkout on the launch pad.

REFERENCES

W.R. Corliss, "Scientific Satellites", NASA SP-133.
The University of Michigan, Department of Aerospace Engineering, Project SCANNER.

APPENDIX A

A.1 FILM PACKAGE DATA AND LOCATION

Table A.1.1
Film Magazines for CWS

Exp	Unit Weight (lbs)	Dimensions* (in)	Volume (in^3)	Earth Return Volume** (in^3)
S052	19	$12\frac{1}{2} \times 9\frac{3}{4} \times 3\frac{3}{16}$	388.5	390
S054	37	25 x 17 x 8	3400	2400
S056	12.5	$18\frac{3}{4} \times 13 \times 4\frac{1}{4}$	1036	875
H-alpha No. 1	12.5	$18\frac{3}{4} \times 12 \times 4\frac{1}{4}$	956.25	875
Total	91.0 lbs		5780.75 in^3	4540 in^3

*This includes all handles and camera lenses.
**This does not include all handles and lenses.

Table A.1.2
Film Magazines for SEWS

S082A	57	21 x 18 x 9*	3402**
S082B	57	21 x 18 x 9	3402
Total	114 lbs		6804

*Vacuum sealed box containing camera and film.
**Earth return volume of the sealed box.

A.2 ARM STRENGTH, SPEED, AND INERTIA CALCULATIONS

A.2.1 Arm Strength

Maximum torque calculation:

Maximum Motor Torque = M_T = 32 oz-in = 2 in-lb

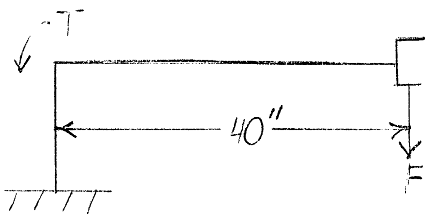
Harmonic Drive Reduction = 160 : 1 = HDR

Output of drive = T = M_T = x HDR = 2 in-lb x 160 = 320 in-lb.

Each concentric motion joint then has a 320 in-lb maximum capacity. This, of course, is much more than a man can exert.

Minimum force configuration calculation:

All joints except the shoulder joint are assumed locked. The shoulder joint motor then is the only one operating and the motor is stalled at peak torque output.



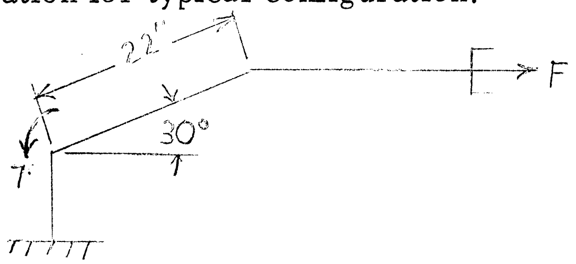
Σ Moments = 0

$T - 40F = 0$

$$F = \frac{T}{40 \text{ in}} = \frac{320}{40 \text{ in}} \text{ in-lb}$$

$F = 8$ lb

Force calculation for typical configuration:



$$\Sigma\ M = 320 \text{ in-lb} - (22 \text{ in} (\sin 30^{\circ})\ F) = 0$$

$$F = \frac{320 \text{ in-lb}}{11 \text{ in}} = 29.1 \text{ lb}$$

A. 2. 2 Arm Inertia and Speed

Another area in which calculations had to be made is that of arm inertia and velocity. The inertia is important in that it will determine the amount of force required to start and stop the motion of the arms. The velocity will determine the response of the arms to the input by the operator.

The force of inertia is found by the following formula:

$$F = M W^2 R$$

where M = total mass of the arm
R = distance from the center of gravity to the shoulder joint
W = angular velocity of the arms

$$R = 21.4'' = 1.78'$$

$$M = 45 \text{ lbs}/32.2 \text{ ft/sec}^2 = 1.4 \text{ slugs}$$

$$W = \frac{(2100 \text{ rev/min})(2\pi)}{(160)(60)} = 1.37 \text{ rad/sec}$$

$$F = (1.4)(1.37)^2(1.78) = 4.7 \text{ lbs.}$$

This force is the maximum inertial force that the arm will ever experience. The 2100 rpm is no-load maximum speed. The (160) represents the harmonic drive gear reduction. The 1.78' is the maximum distance the center of gravity will ever get from the shoulder joint.

With a force feedback gain constant of around 35, this inertial force will be greatly reduced to about 2 oz. This will be the only inertia felt by the operator. Friction effects have not as yet been analyzed.

The velocity capacity of the arm will be 66 in/sec fully extended, and 19 in/sec in the fully retracted (docking) configuration. These are greater than the normal human arm velocity, for the anticipated working volume, and therefore well suited for this subsystem application. For optimum response, the velocity should be near 35 in/sec for all motions.

A. 3 SUBSYSTEM REQUIREMENTS

The manipulator subsystem of REMUS will require the following support from each of the subsystems listed.

All power requirements will be run off the teleoperator's 28 volt system and the manipulators will not be operated while the tethers are in use. The power figures are outlined in the following table.

Table A. 3. 1

Item	Peak	Average
Manipulators	1854 watts	50 watts
Tethers	60 watts	20 watts
Amplifiers	2 watts	nil
Total	1916 watts	

In order to operate the Teleoperator's manipulators away from the Skylab, a considerable number of communication links are required. These have been broken down and are found in the following table.

Table A. 3. 2

No. of Channels	Description of Signal	Source
28	Force Feedback	Teleoperator
28	Manipulator Control	Skylab
15	Digital ON/OFF (tethers)	Skylab
15	Digital ON/OFF (solenoid brakes)	Skylab
21	Engineering Telemetry 14 motor temperatures 6 tether potentiometers 1 position error signal	Teleoperator

Another very important subsystem that needs analysis is the weight break-down for the entire manipulator subsystem. This is shown in the following table.

Table A. 3. 3

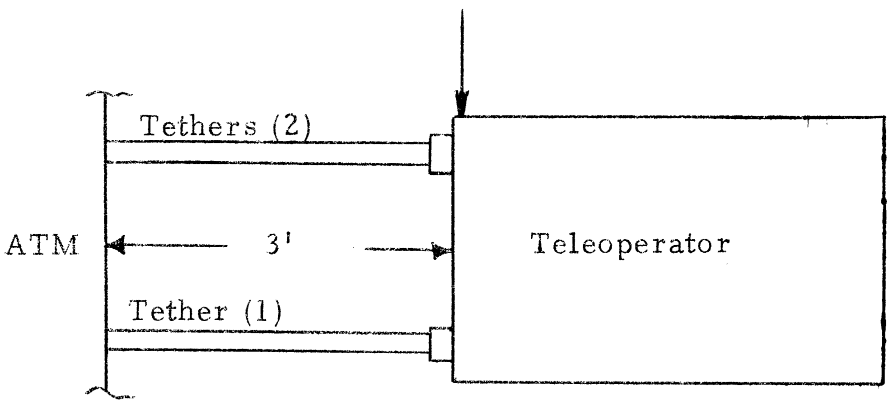
Item	No. Users	Location	Weight (lb)
Model 301 Micro switch Honeywell DC Motors	12	Six shoulder joints and six wrist joints	54
T-1218 Inland DC Motor	2	End Effector	.3
Harmonic Drives	14	All Joints	6
Parallel Jaws	2	End Effector	2
Gearbox	2	End Effector	2
Bearings	26	All Joints	5
Potentiometers	14	All Joints	.7
Force Transducers	14	All Joints	7
Cable and Connectors			
4" ID Aluminum Tubing, 1/8" thick	2	Upper and lower Arms	12
Housings	14	All Joints	21
Amplifiers	17	Spacecraft	34
Tethers	3	Spacecraft	40
TOTAL			184 lbs

Because of the space environment, thermal control in the arms must be dealt with in a very special way. All motors will be hermetically sealed so that heat generated in each motor will be conducted to the joint housings and transferred to space. This sealing will also cause the motors to lose needed warmth when they are not in operation and therefore, Electrofilm Heaters will be used around each motor to compensate for the wide variation in incident radiant energy between light and shadow operations. The temperatures of the motors will be monitored and the heaters switched on when any of the motor temperatures in one arm drops below a preset temperature. These heaters can also be used during refurbishment and flight to and from the work site.

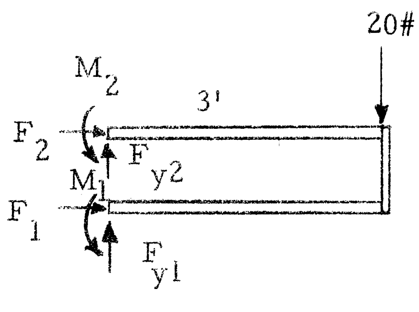
Since the tether motors will be constantly exposed to space, an attempt is being made to manufacture motors that will not need to be heated. This brings up the subject of problems encountered during this project.

A.4 TETHER STRENGTH CALCULATIONS

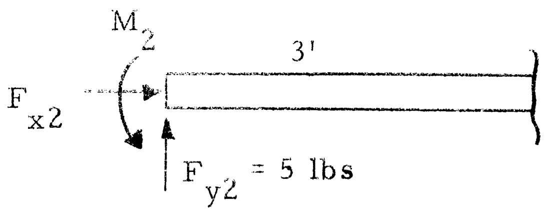
In determining the bending moment that the tethers must withstand, a series of tests have shown that the maximum force a normal man can comfortably exert in a vertical direction is approximately 20 pounds. This maximum force has been used as the optimum force exerted by the manipulator slave arms at a distance of 3 feet.



The force diagram for this problem is:



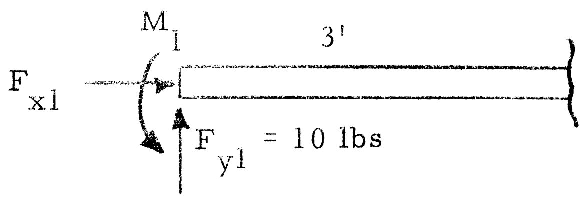
The result is that the problem is statically indeterminant. Therefore, in analyzing this case, it was assumed that the 20# force was equally dispersed by the two top tethers and the lower tether, that is, each top tether sees F_{y2} = 5 lbs and the lower tether sees F_{y1} = 10 lbs*. Then



$$M_2 = F_{y2}(3')$$

$$M_2 = 5 \text{ lbs}(3') = 15 \text{ ft lbs}$$

and



$$M_1 = F_{y1}(3')$$

$$M_1 = 10 \text{ lbs}(3') = 30 \text{ ft lbs}$$

---

*Because of this assumption, the values of M_1 and M_2 are taken to be lower than maximum. Therefore, stronger tethers were chosen.

A.5 PROBLEMS

With this type of design project, problems are encountered that cannot be dealt with in the short amount of time alotted for this study. These problems should be mentioned, however, if only to bring them to the attention of others working in this field.

Probably the largest area for improvement is that of the DC motors used in the joints of the arms. The weight of these arms is too large and the motors are responsible for this. What is needed is a low weight, low rpm, very low inertia motor. These along with the harmonic drives would require the most development. The harmonic drives have high internal friction which decreases the response of the arms. This friction is not constant, but varies between a high and low value. This is the reason the signals have been phased 90^{o} in order to attempt to average these extremes.

Considerable development is needed in the area of video coverage for the work site. Presently, problems have been anticipated with regards to clearness and depth perception as well as possible conflicts when the arms enter the field of vision.

The force transducers used in the joints for the force feedback were developed by Mr. Flatau of Brookhaven National Lab and according to him, they too, need more work. The potentiometers, solenoid brakes and bearings are generally off the shelf items, but could use work to reduce size and weight and increase performance in a space environment.

Arm response is definitely nowhere near optimum. The end effector is limited to certain types of tasks and ideally should be increased in its degrees of freedom of motion.

Tether problems include the reduction of working area due to the distance taken up by the motor drives for lateral and vertical movement. These motors also need work since they should be strong, small, light, and ideally they would operate without being hermetically sealed. They would need low power requirements and slow rotational shaft speeds. Design work must be done on the electrically locking ball joints. Again, low power and high strength are needed. Testing must be done to determine what size clamp must be used to lock the Teleoperator during docking.

The counterbalancing problem will have to be solved in order to test the equipment before being flown. No matter how easy the operation is made, the astronaut will need many hours of practice to get used to this system.

If full effort was applied, the technology would develop fast enough to assure a highly capable and responsive manipulator system to fly in Skylab B.

APPENDIX B
AREAS FOR FURTHER INVESTIGATION

B.1 MECHANICAL LINKAGE BETWEEN CAMERAS II AND III:

The mechanical linkage provides synchronous operation for cameras II and II for stereo. There are other ways to effect this synchronous mode, such as employing closed-loop servo-operated motors on each camera unit. However, this seems a lot more complicated than necessary. The mechanical link is the simplest method to effect. Further investigation should be made, however, as to the best method for synchronous operation.

One consideration is whether to use brushless DC motors with a solid space lubricant, or to use hermetically sealed motors. Brushless DC motors are lighter and consume less power, but their mission life is dependent on the quality of the lubricant. Hermetically sealed motors weigh more, and consume more power than the brushless DC motors, and if a seal should rupture, these motors would soon burn up. Brushless DC motors seem to be the better of the two.

A second consideration is whether to attempt to drive the motors in each camera unit concurrently, with a load sharing device in the linkage, or to use a clutch/differential device which will disengage the motors in the camera enclosures and employ a third set of motors to drive the zoom, focus and aperture mechanisms of each camera unit. The clutch/differential mechanism should be avoided as it would complicate matters should camera III have to be removed as backup for camera I. Whether or not a load sharing device would put undue strain on the motors of one camera unit will have to be determined. Laboratory examinations should be made and other possible methods investigated.

B.2 USE OF THE VIDEO SYSTEM AS PART OF A RANGING SYSTEM

It is possible to determine the Teleoperator's range from its docking site by utilizing information on the cameras' aperture openings, zoom lens configurations, and the focal lengths of the lens. This information would have to be measured within the camera housings, relayed to Skylab, and run through a computer to provide ranging data. This process is analytical and simple to effect in theory. However, it is difficult to do in practice because all this information must be obtained with the camera in focus. Therefore, unless we are to rely on the operator's vision to keep the cameras in focus, which would be very imprecise, we would need an automatic focus with the resultant increases in weight and complexity. A ranging system would be an added safety feature; this area should be further investigated.

B.3 STEREO PRESENTATION SCREEN

An investigation should be made as to what material would best present the optically combined images of cameras II and III. Care must be taken to assure that the light from the monitors is not depolarized before it reaches the operator. It may be necessary to present virtual images if a suitable material cannot be found.

B.4 STEREO OPTICS

A further examination of which stereo-producing method to utilize should also be made. We want to avoid having to constantly update the lines of fixation of cameras II and III. This method would provide the best and most accurate depth perception, but would also be the most difficult method to effect. We have chosen the parallel-aimed camera system, as it is the least complicated and provides good depth perception. Laboratory tests should be run.

Human factors tests should be run to determine which method if viewing the optically combined images would be least fatiguing to the operator. In the next year, Marshall Space Flight Center will be conducting tests in this area.

Ideally, the baseline separation of cameras II and III should be larger, but we were constrained by the shoulder joints of the manipulators. If the Teleoperator is going to "fly," this separation should be increased to improve the stereo vision capcity. If the baseline separation is made large enough, it may be possible to eliminate the drop-down lens on camera II (part of camera back-up system).

SPECIFICATIONS

1. Camera Tube:

Electrical	
- Preamp Bandwidth	16 mc within 2 db
- Preamp Transimpedance	150 K
- Focus Coil Current	constant within ± .25% over full temp range
Photosurface	
- Silicon	
- Diameter	1 inch
- Length	4.25 inches
Environmental	
- Operating Temperature	-50°C to +50°C
- Humidity	95%

2. Control Units:

Electrical	
- Power Source	+28 VDC nominal
- Frame Rate	30 fps 2:1 pos interlace
- Line Rate	525 lines/frame
- Aspect Ratio	4:3 (1:1 optional)
- Sweep Linearity	± 2%
- Video Bandwidth	4 MHz
- Aperture Correction	18 db available
- Automatic Gain Control	40 db
- Video Output	Composite 1 volt peak-to-peak
Environmental	
- Operating Temperature	-50°C to +100°C
- Humidity	95%

3. Zoom Lenses:

- Focal Length	12 to 120 mm
- Aperture	f/2.8 to f/22
- Object Angular Field	7°30' to 67°
- Total Length	9.61 inches
- Shortest Focusing Distance	2.5 ft
- Weight	3 lb 10 oz

Component	Power Each (Watts)	Power Total (Watts)	Weight Each	Weight Total (lb)	Size (in)
Cameras (3)	4.0 ea	12.0	10.0	2.0	1.7 dia x 6.4 length
Zoom Lenses (3)	9.0 ea	27.0	316 10 oz	10.9 lbs	6 x 6 x 9.6"
Control Units (3)	12.0 ea	24.0	4.5 lb	13.5	5x25 x 6.0 x 5.7
Lights & Light Controls (3)	5.0 ea	15.0	3.0 lb	9.0	2.0 (dia) x 2.0
Platform	---	10.0	--	30.0	20 x 16
Cabling	---	---	---	6.0	1/2 dia
Camera Enclosures (3)	---	---	4.0 lb	12 lb	6 x 6 x 16"
	Peak Power	70.0	Total Weight	83.4	
	Ave. Power	55.0			

Figure B.1 Power, Weight, and Size Estimates for Video Subsystem

APPENDIX C

C.1 HARDWARE SPECIFICATIONS

A. Reaction Wheels

The selection of reaction wheels should be based on an estimate of the magnitude and direction of disturbance torques. For this mission, however, there is another restraint, namely, use of the reaction wheels to effect a desired attitude change. Operating in this mode, the wheels will be spun up to produce a torque, and hence a body rate, and then despun to its original speed to null the rate. Therefore, the size of the wheels will be calculated on an assumed desired vehicle rate. Let us suppose that the reaction wheels should be capable of producing a body angular acceleration of 1 deg/sec^2 (.00179 rad/sec^2) about the z-axis.

Then, summing torques,

$$I_{ZZ}\ \dot{\omega}_s = \dot{H}_\omega$$

where $\dot{H}_\omega$ is the rate of change of the wheel's angular momentum. Separating the variables and integrating both sides of the above equation yields

$$I_{ZZ}\ \omega_s\ t_B = H(t_B) - H(t_0)$$

where t_B = acceleration time = 7 sec (i. e. angular rate will be 7 deg/sec at end of acceleration)

The left side of the above expression is numerically

$$(5.25)(1.79)(7) \times 10^{-2}\ \frac{\text{slug-ft}^2}{\text{sec}} = 0.658\ \frac{\text{slug-ft}^2}{\text{sec}}$$

The wheels must be capable of delivering this much "extra" momentum to the spacecraft. In equation form, we have

$$C(\omega_{tB} - \omega_o) = 0.658\ \frac{\text{slug-ft}^2}{\text{sec}}$$

Now consider disturbance. Typical of these would be

(a) Gravity gradient
(b) Earth's magnetic field
(c) Solar pressure
(d) Meteorite impact

However, these disturbances are negligible for this mission

The following reaction wheel was selected to satisfy the requirements imposed upon it.

Reaction Wheels

Rotor inertia	0.014 slug-ft^2
Momentum	1.456 at 1000 RPM
Stall torque	2.0 oz-in
Tachometer	Magnetic pulse counter; different slug gaps for speed and direction of rotation
Mounting	Flat base
Overall dimension	7.5" O.D. 3.4" high
Weight	10.1 lbs
Synchronous speed	1500 RPM

Although these specifications will satisfy the restraints, a trade-off study should be made of rotor inertia and wheel speed to determine the optimum reaction wheel.

B. Cold Gas Reaction Control System

Nitrogen was chosen as the inert gas for it's moderate specific impulse. The other specifications are from studies of the current state of the art.

Cold Gas Reaction Control System

Fuel	N_2
Number of thrusters	16
Tank pressure (nominal)	4000.0 psia
Tank volume	864.3 in^3
Thrust	0.5 lbf
Specific impulse	14.1 sec
Power required* (total)	117.5 watts
Weight*	25.83 lbs (fuel only)

*See Appendix C.2.

C. Rate Gyro

The rate gyro package was chosen mainly on estimated maximum input angular rate. Another important basis was linearity and drift rate, which it is felt are optimized with the following selection.

Rate Gyro

Input maximum rate	20 deg/sec
Overall dimensions	2.5" diameter
	4.7 " high
Weight	1.4 lbs
Heater power	10.0 watts
Motor power	start 7.5 watts
	run 3.5 watts
Linearity	± 0.5% of full scale
Random drift	0.005 deg/hr

D. Rate Integrating Gyro

The selection of the rate integrating gyro package is critical, for it will act as an inertial reference for stabilization and docking maneuvers. The gyro should be capable of large excursion off null, yet still retain high accuracy. Although some of these gyros are capable of 60 degree input angular excursions, their accuracy characteristics are not acceptable. The following package was selected.

Rate Integrating Gyro

Input angular freedom	± 10 degrees
Gimbal freedom	± 4.6 degrees
Angular momentum	1×10^5 gm-cm^2/sec
Operating temperature	180°F
Gimbal pckoff sensitivity	12.5 volts/rad
Heater configuration	
Operating	
Voltage	28 volts D.C.
Power	26.5 watts
Warmup	
Voltage	28 volts D.C.
Power	50 watts
Spin Motor	
Excitation	
Voltage	26 volts (line-line-3φ
Frequency	400 cps
Weight	1.1 lbs
Size	1.65" by 2.150"

C.2 FUEL REQUIREMENTS

A proposed retrieval and inspection mission is used as the basis of the following calculations. The mission is accomplished by using the 0.5 pound thrusters. The maneuvering is through a series of pure translations and pure rotations, which assumes an uncoupling of motion. This assumption is valid if the angular rates are kept low.

A. Linear translations - a series of 32 ΔV changes of $\pm$ 0.5 feet/second.

To acquire these translations, the following thrusters will be used (see Figure 4.1).

+x	3, 7, 11, 15
-x	1, 5, 9, 13
+y	6, 14
-y	2, 10
+z	12, 16
-z	4, 8

To calculate fuel requirements, the following equation has sufficient accuracy.

$$\Delta V = g\, I_{sp} \ln \frac{M_1}{M_2} - g\, t_B$$

If there are no altitude changes this equation reduces to

$$\Delta V = g\, I_{sp} \ln \frac{M_1}{M_2}$$

or

$$\frac{M_1}{M_2} = e^{\frac{g\, I_{sp}}{\Delta V}} \qquad M_2 = M_1 \left(1 - e^{\frac{g\, I_{sp}}{\Delta V}}\right)$$

or, the weight of fuel required for translation is given by

$$W_2 = W_1 \left(1 - e^{\frac{-g\, I_{sp}}{\Delta V}}\right)$$

then, for

$\Delta V = 0.5$ fps $\qquad g = 32.2$ ft/sec^2 $\qquad I_{sp} = 14.1$ sec

$$W_1 = 650 \text{ lbs} \qquad W_2 = 650 \left(1 - e^{\frac{-(32.2)(14.1)}{0.5}}\right) = 650\,(1 - .9989)$$

$$W_2 = (.0011)(650) = 0.715 \text{ lbs}$$

But there are 32 such ΔV changes, therefore the total required weight is

$$W_{tot} = 32\ (0.715)\text{lbs} = 22.85\ \text{lbs.}$$

The total burn time is found from

$$\frac{\text{Total Impulse}}{\text{Total Weight}} = 14.1\ 1\ \frac{2\ t_B}{22.85}$$

$$t_B = 161\ \text{sec}$$

$$\text{Total impulse} = 2\ t_B = 2(161) = 322\ \text{lb-sec}$$

The tank size is then given by

$$\frac{\text{Total Impulse}}{\text{Total Volume}} = 0.5 \qquad \text{Total volume} = \frac{322\ \text{lb-sec}}{0.5\ \text{lb-sec}}\ \text{in}^3$$

$$\text{Total volume} = 644\ \text{in}^3$$

and the total required power is given by

$$\frac{\text{Total Impulse}}{\text{Total Power}} = 3.1 \qquad \text{Total power} = \frac{322}{3.1}\ \text{watts}$$

$$\text{Total power} = 104\ \text{watts}$$

<u>Rotational Fuel Requirements</u>

Assuming the speeds of the reaction wheels are constant and near zero, the rotational equations of motion are:

$$I_{xx}\ \ddot{\phi} = L_x \qquad \dot{\phi}\ \ \frac{L_x}{I_{xx}}\ \Delta t$$

$$I_{yy}\ \ddot{\theta} = L_y \qquad \dot{\theta} = \frac{L_y}{I_{yy}}\ \Delta t$$

$$I_{zz}\ \ddot{\psi} = L_z \qquad \dot{\psi} = \frac{L_z}{i_{zz}}\ \Delta t$$

For rotations about the x-axis, thrusters 8 and 12 or 4 and 16 are used for positive and negative rotations, respectively (see Figure 4.1). Thrusters 2 and 14 or 6 and 10 are used in backup only. In the primary mode the control torque is:

$$L_x = \frac{(21.5\ \text{in})(2)(.516)(1\ \text{ft})}{12\ \text{in}} = 1.79\ \text{ft-lb.}$$

For rotations about the y-axis, thrusters 3, 7, 8, and 13 or 1, 5, 11, and 15 are used for positive and negative rotations, respectively. The control torque is:

$$L_y = \frac{4(.516)(3.5\ \text{in})(1\ \text{ft})}{12\ \text{in}} = .583\ \text{ft-lb.}$$

For rotations about the z-axis, thrusters 1, 7, 8, and 15 or 3, 5, 11, and 13 are used for positive and negative rotations, respectively. The control torque is:

$$L_z = \frac{4(.516)(21.5\ \text{in})(1\ \text{ft})}{12\ \text{in}} = 3.58\ \text{ft-lb.}$$

For fuel calculation purposes angular rates are calculated for a burn time of one second. They are as follows:

$$\dot{\phi} = \frac{L_x}{I_{xx}} \Delta t = \frac{1.79\ \text{ft-lb}}{41.2\ \text{slug-ft}^2} (1)\ \text{sec} = .0435\ \text{rad/sec} = 2.49\ \text{deg/sec}$$

$$\dot{\theta} = \frac{L_y}{I_{yy}} \Delta t = \frac{.583\ \text{ft-lb}}{48.6\ \text{slug-ft}^2} (1)\ \text{sec} = .012\ \text{rad/sec} = 6.88\ \text{deg/sec}$$

$$\psi = \frac{L_z}{I_{zz}} \Delta t = \frac{3.58\ \text{ft-lb}}{52.5\ \text{slug-ft}^2} (1)\ \text{sec} = .0682\ \text{rad/sec} = 3.92\ \text{deg/sec}$$

A sample inspection mission includes the following rotational requirements:

1. About the x-axis:

   5 rotations of 90^o
   2 rotations of 45^o

Total of 14 rotational impulses. Each impulse has a duration of one second and utilizes two thrusters. Total impulse is 14 lb-sec.

2. About the y-axis:

   3 rotations of 90^o
   2 rotations of 45^o

Total of 10 rotational impulses. Each impulse has a duration of one second and utilizes four thrusters. Total impulse is 20 lb-sec.

3. About the z-axis:

2 rotations of 45°

Total of 4 rotational impulses. Each impulse has a duration of one second and utilizes four thrusters. Total impulse is 8 lb-sec.

Total impulse for all rotational requirements is 14 + 20 + 8 = 42 lb-sec.

$$\text{Total weight of fuel} = \frac{\text{Total Impulse}}{\text{Specific Impulse}} = \frac{42 \text{ lb-sec}}{14.1 \text{ sec}} = 2.98 \text{ lb}$$

$$\text{Total volume} = \frac{\text{Total Impulse}}{\text{Specific Volume}} = \frac{42 \text{ lb-sec}}{.50 \dfrac{\text{lb-sec}}{\text{in}^3}} = 84 \text{ in}^3$$

$$\text{Total power} = \frac{\text{Total Impulse}}{\text{Specific Power}} = \frac{42 \text{ lb-sec}}{3.1 \dfrac{\text{lb-sec}}{\text{watt}}} = 13.5 \text{ watts}$$

In sum, the total requirements for rotation and translation are:

Total weight of fuel	25.83 lbs
Total impulse required	364 lb-sec
Total tank volume	728 in^3
Total power required	117.5 watts

C.3 EQUATIONS OF MOTION AND SIMULATION CONSIDERATIONS

Greenwite (Reference 6, Section 4) shows that for a reaction wheel controlled satellite the governing equations are

$$
\begin{aligned}
P I_{xx} + (I_{zz} - I_{yy})QR &= -C_x \Omega_x + C_y \Omega_y R - C_z \Omega_z Q + L_{Dy} \\
Q I_{yy} + (I_{xx} - I_{zz})PR &= -C_x \Omega_x R - C_y \Omega_y + C_z \Omega_z P + L_{Dy} \qquad (1) \\
R I_{zz} + (I_{yy} - I_{xx})QP &= C_x \Omega_x Q - C_y \Omega_y P - C_z \Omega_z + L_{Dz}
\end{aligned}
$$

where P, Q, R are the body rates; I_{xx}, I_{yy}, I_{zz} are REMUS's moments of inertia; Ω_x, Ω_y, Ω_z are the wheels angular velocity; and L_{Dx}, L_{Dy}, L_{Dz} are disturbance torques.

A. Stabilization

Let's restrict ourselves to small P, Q, R, which will be the case for maintaining a desired attitude. Defining a reference axis at this attitude and employing the Euler angles ϕ, θ, ψ, the relation between P, Q, R and ϕ, θ, ψ is given by

$$\psi = Q \frac{\sin \phi}{\cos \theta} + R \cos \phi \sec \theta$$

$$\theta = Q \cos \phi - R \sin \phi$$

$$\phi = P + Q \sin \phi \tan \theta + R \cos \phi \tan \theta$$

Then for small angles ($< 8^{\circ}$), the above equations can be approximated by

$$\dot{\psi} = R$$

$$\dot{\theta} = Q$$

$$\dot{\phi} = P$$

Perhaps a digression is in order. We need only look at equation (1) to conclude that the equations are badly coupled. The hope, here, is to build a mathematical model that can accurately represent equation (1). The final justification is, of course, through simulation. Bearing this in mind, we continue this analysis. By introducing the above approximations into equation (1)

$$\ddot{\phi} I_{xx} + (I_{zz} - I_{yy}) \dot{\theta} \dot{\psi} = -C_x \dot{\Omega}_x + C_y \Omega_y \dot{\psi} - C_z \Omega_z \dot{\theta} + L_{Dy}$$

$$\ddot{\theta} I_{yy} + (I_{xx} - I_{zz}) \dot{\phi} \dot{\psi} = -C_x \Omega_x \dot{\psi} - C_y \dot{\Omega}_y + C_z \Omega_z \dot{\phi} + L_{Dy}$$

$$\ddot{\psi} I_{zz} + (I_{yy} - I_{xx}) \dot{\theta} \dot{\phi} = C_x \Omega_x \dot{\theta} - C_y \Omega_y \dot{\phi} - C_z \dot{\Omega}_y + L_{D_z}$$

Let's neglect products of Euler angles because they are small. Also define

$C \Omega$ = wheel angular momentum = H

$C \dot{\Omega}$ = rate of change of angular momentum = H

Then the equations become

$$\ddot{\phi} I_{xx} = -\dot{H}_x + H_y \dot{\psi} - H_z \dot{\theta} + L_{Dx}$$

$$\ddot{\theta} I_{yy} = -H_x \dot{\psi} - \dot{H}_y + H_z \dot{\phi} + L_{Dy}$$

$$\ddot{\psi} I_{zz} = H_x \dot{\theta} - H_y \dot{\phi} - \dot{H}_z + L_{Dz}$$

It is readily agreed that the resulting equations appear very limited by their assumptions. However for purposes of preliminary design, it proves convenient to artifically uncouple the equations of motion as if there were three independent systems instead of one highly coupled one. Thus, one proceeds with the hope that a synthesis based on the separate set will be a satisfactory approximation to a synthesis based on the complete system. Needless to say, the final design must be carefully validated by computer simulation of the complete non-linear system.

Figure C.3.1 is a proposed analog simulation of REMUS, based on the above results. The coupling terms are introduced into the appropriate channel as disturbance torques, as would be the case in the real situation. The constants K_m, τ_m, and C are determined by the reaction wheel specifications. The remaining constants K_R, K_I, K_A will be determined by desired response, i.e, rise time, damping, settling time.

B. Rotational Maneuvers

For rotations, where ψ, ϕ, θ are no longer small angles, equations (2) break down and are no longer applicable. As mentioned earlier, the reaction wheels will not be used during large angle rotational maneuvers (though, they could be in the event of thruster failure). Thus, their angular momentum will be a constant. Let's denote this by

$$K_x = H_x \qquad K_y = H_y \qquad K_z = H_z$$

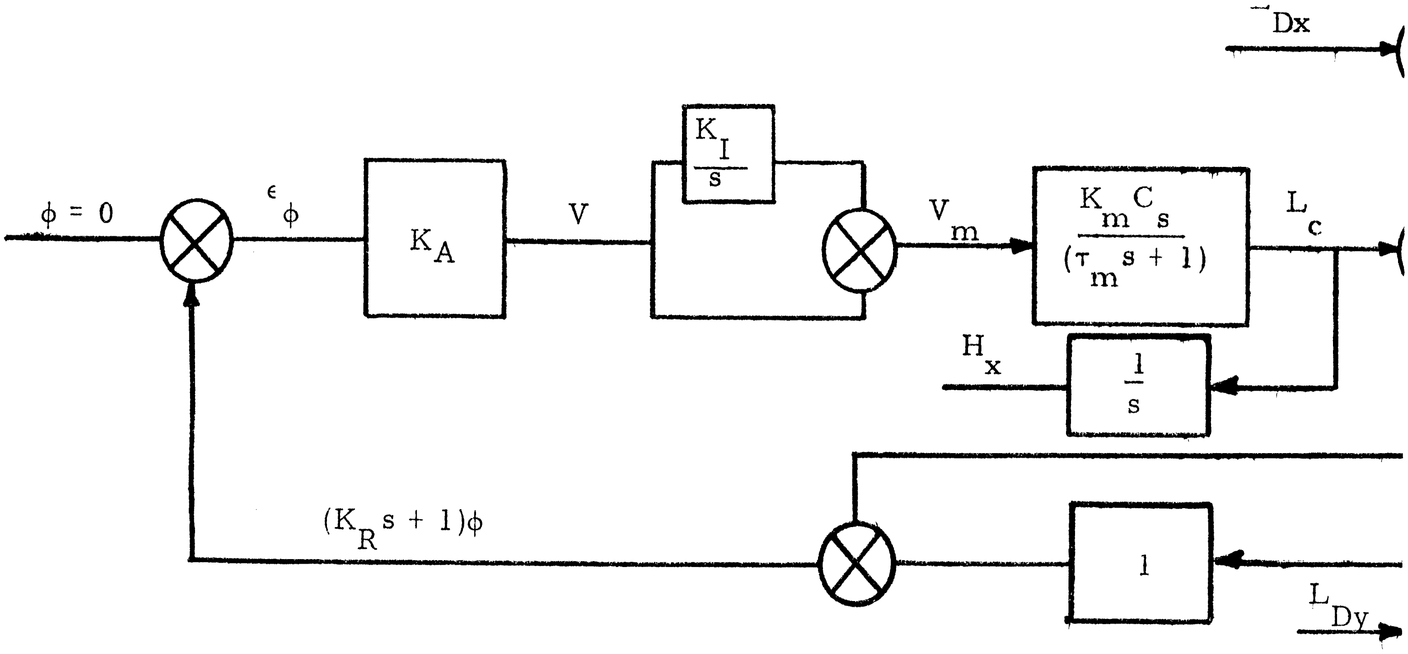
then equations (1) become

$$P\, I_{xx} + (I_{zz} - I_{yy})\, QR = K_y\, R - K_z\, Q + I_{cx}$$

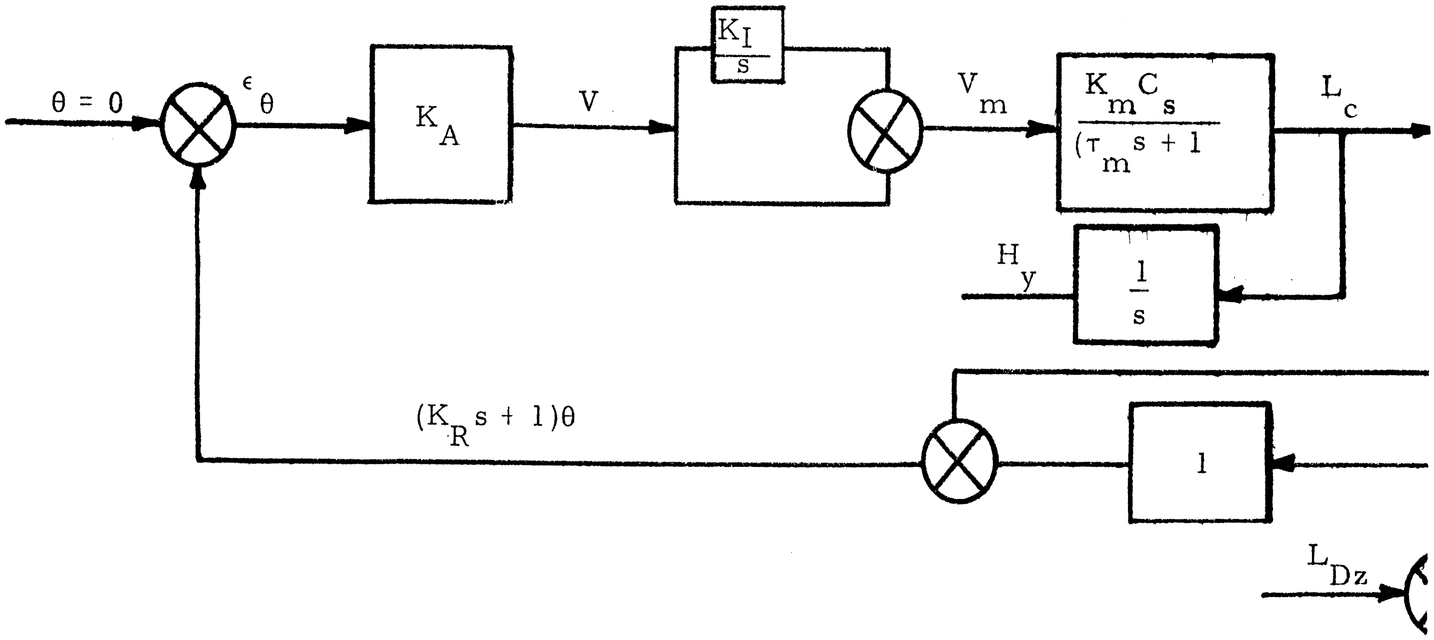
$$Q\, I_{yy} + (I_{xx} - I_{zz})\, PR = -K_x\, R + K_z\, P + L_{cy}$$

$$R\, I_{zz} + (I_{yy} - I_{xx})\, PQ = K_x\, Q - K_y\, P + L_{cz}$$

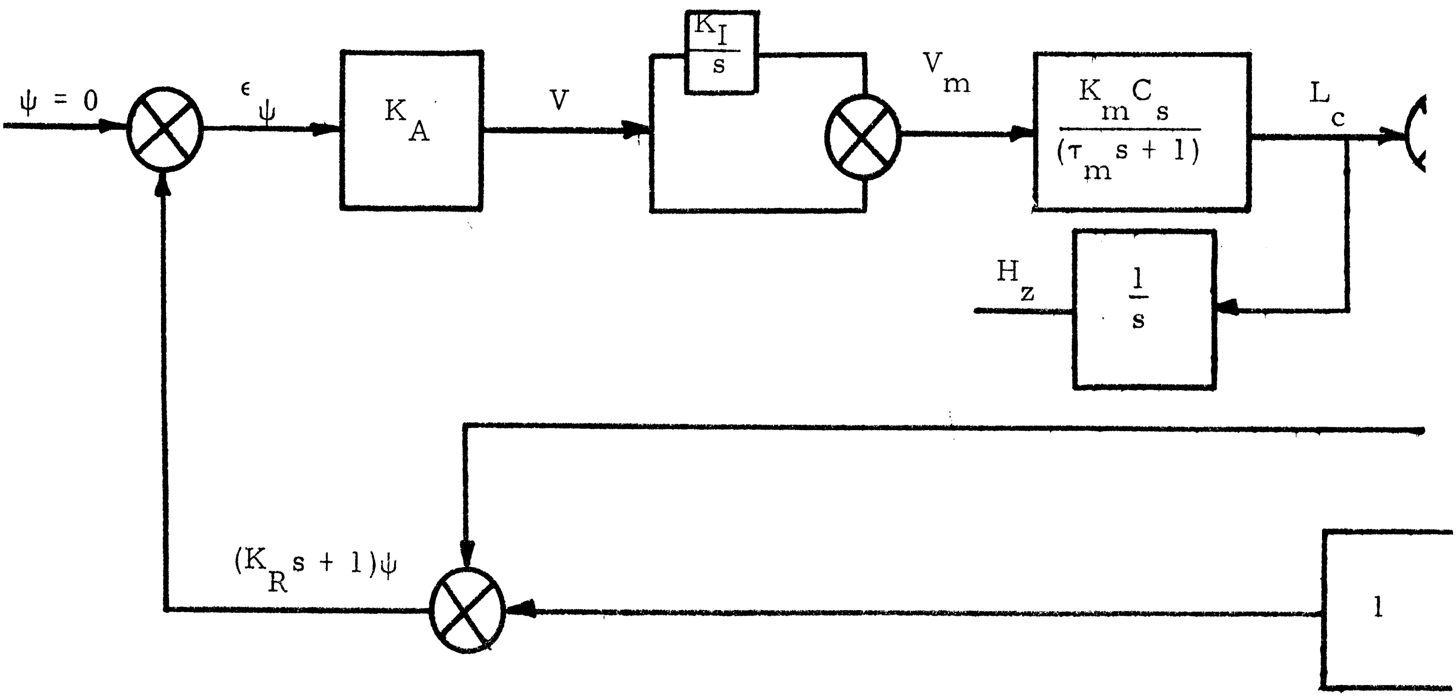
Again, the equations are very badly coupled. There are no artificial ways of uncoupling these equations. REMUS will have to be simulated to determine the correct thruster firing sequence.



Dx
φ = 0
ϵ φ
K A
V
K I / s
V m
K m C s / (τ m s + 1)
L c
H x
1 / s
(K R s + 1)φ
1
L Dy



θ = 0
ϵ θ
K A
V
K I / s
V m
K m C s / (τ m s + 1
L c
H y
1 / s
(K R s + 1)θ
1
L Dz



ψ = 0
ϵ ψ
K A
V
K I / s
V m
K m C s / (τ m s + 1)
L c
H z
1 / s
(K R s + 1)ψ
1

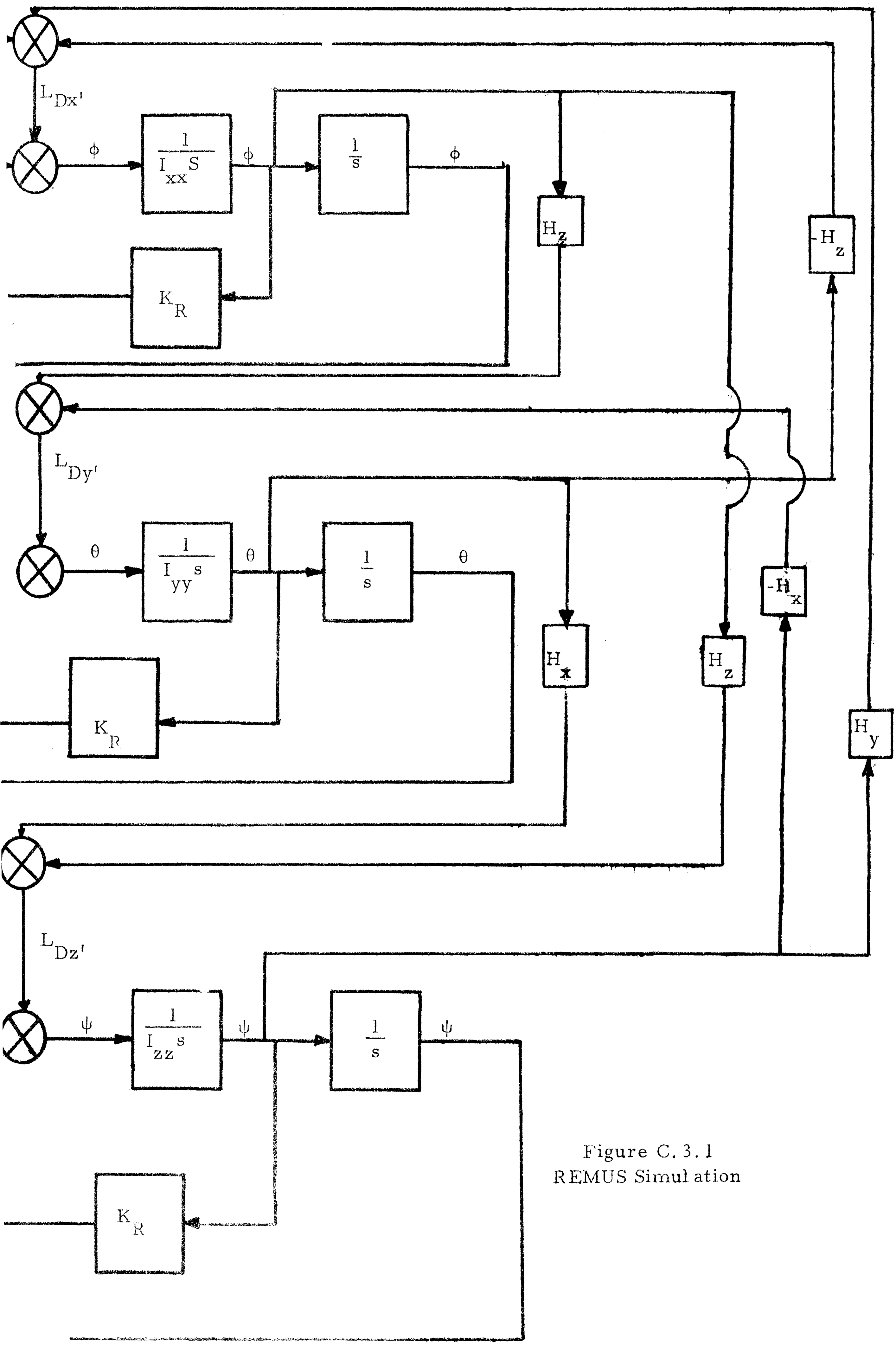


Figure C.3.1
REMUS Simulation

APPENDIX D
COMMUNICATIONS

D.1 BANDWIDTH CALCULATIONS AND FREQUENCY ASSIGNMENTS

D.1.1 Data Link

Information Bandwidths

Number	Source	Bandwidth
2	Video	4.0 MHz
28	Manipulators	50.0 Hz
6	Attitude & Control	50.0 Hz
21	Manipulators	0.1 Hz
4	Power	0.1 Hz
5	Attitude & Control	0.1 Hz
36	Structures	0.1 Hz
4	Thermal	0.1 Hz

Subtotals:

2- 4.0 MHz signals
34- 50.0 Hz signals
70- 0.1 Hz signals

Modulation Scheme:

AM - 4.0 MHz signals
FM/AM- 50.0 Hz signals
PAM/FM/AM- 0.1 Hz signals

for PAM:

f_o = break frequency = 0.1 Hz
cutoff rate = 18-24 db/octave
RMS error = 10%

For the above characteristics:

u = sampling frequency/break frequency = 4
f_s = sampling frequency = uf_o = 0.4 Hz
v = number of channels = 70
f_p = pulse repetition frequency = vf_s = 28 Hz

For FM:

f_o = 50 Hz
RMS error = 1%

For the above characteristics:

D = deviation ratio = 5
$f_s = Df_o$ = 250 Hz
B = IF bandwidth/f_s = 3.5 for 1% RMS error
B_{IF} = IF bandwidth = Bf_s = 875 Hz per channel
Guardbands of 1.125 KHz per channel
Total B_{IF} = 2 KHz per channel
v = 35 channels
B_{IF} Total = v(Total B_{IF}/channel) = 70 KHz

Channel 1 Composite Baseband Signal

TV signal =	4 MHz
Guardband =	180 KHz
FM input =	70 KHz
Total Bandwidth	4.25 MHz = B_m

For AM:

$B_{IF} = 2B_m$ = 8.5 MHz

Channel 2 TV Signal

TV signal = 4 MHz = B_m
AM $B_{IF} = 2B_m$ = 8 MHz

RF Carrier Frequencies:

Channel 1 - 200 MHz
Channel 2 - 211 MHz

D.1.2 Command and Control Link

Information Bandwidths

Number	Source	Bandwidth
28	Manipulators	50.0 Hz
6	Attitude & Control	50.0 Hz
1	Thruster Control	100 bits/sec
1	Commands	120 bits/sec

Subtotals:

34- 50.0 Hz
1- 100 bits/sec
1- 120 bits/sec

Modulation Scheme:

FM/AM- 50.0 Hz signals
PCM/FSK/AM- coded signals

For FM:

$f_o = 50$ Hz
RMS error = 1%

For the above characteristics

$D = 5$
$f_s = Df_o = 250$ Hz
$B = 3.5$ for 1% RMS error
$B_{IF} = Bf_s = 875$ Hz per channel
Guardbands of 1.125 KHz per channel
$v = 34$ channels
B_{IF} Total = $v(B_{IF}$/channel) = 70 KHz

For PCM/FSK

B_{IF} = bit rate
Thruster Control at 100 bps = 100 Hz
Commands at 120 bps = 120 Hz

Channel 3 Composite Baseband Signal

The PCM/FSK Command signal is centered at 10 KHz with a 120 Hz bandwidth. The FM subcarrier frequencies start at 101 KHz with the last channel at 167 KHz. The Thruster Control PCM/FSK signal is then centered at 169 KHz giving a bandwidth of approximately 170 KHz before AM modulation. After AM modulation the signal bandwidth is

$$B_{IF} = 2(170 \text{ KHz}) = 340 \text{ KHz},$$

RF Carrier Frequency:

Channel 3 - 193 MHz

D.2 LINK CALCULATIONS

The following is a link calculation for the channel 1, the link from the Teleoperator to Skylab, with the greatest bandwidth. A worst case is taken with the following characteristics.

Range = one statute mile
Antenna temperature = 1300 Degrees Kelvin
Receiver noise figure = 4

For channel 1:

Maximum frequency = 204.25 MHz
IF bandwidth = 8.5 MHz

For the Teleoperator Radio Subsystem:

Transmitted power = -3db
Antenna gain = 0db
Polarization and system losses = 3.5 db

For the Skylab Radio Subsystem:

Antenna gain = 0db
System losses = .5 db

Link Calculation	
Transmitter Power	-3db
Skylab Antenna Gain	0db
Teleoperator Antenna Gain	0db
Total Polarization & System Losses	4db
Free Space Loss	80db
Received Power	-87db
Receiver Noise	-122db
S/N at Receiver	35db
Required S/N for FM above threshold	10db
Margin	25db

At normal operating ranges, a similar calculation shows the Free Space Loss to be less than 40db, giving a margin of more than 65db. This margin, however, may be considerably reduced if multipath interference proves to be a serious problem.

D.3 SKYLAB ANTENNA CONFIGURATION

Antenna placement on Skylab is a major problem. It is desirable to have the capability to maneuver the Teleoperator into any location. The Skylab structure can be divided into three major sections; these being the OWS and IU area, the CSM, MDA, and underside ATM area, and the upper ATM area.

For coverage in the OWS area, two deployable loop type antennas mounted on booms will be used. These antennas will be located in the aft portion of the forward skirts, behind the solar array assemblies. Deployable by an internal command, the antennas extend aftward at an angle of approximately 45° with the centerline of the OWS. This affords good coverage around the OWS and IU, and backup coverage in the upper area of the ATM and in the vicinity of the CSM.

In the CSM, MDA, and lower ATM area, four low-profile spiral antennas are equally spaced around the forward perimeter of the MDA. The antennas are potted in a dielectric to prevent breakage. The orientation of these antennas affords virtually uniform coverage from the forward end of the IU to the aft of the CSM in the docked configuration.

Coverage in the area of the upper ATM is a special case. The ATM canister is surrounded by a dish like structure, and radiation patterns from the two aft-mounted boom antennas will not intercept the Teleoperator antenna patterns, and vice versa if the vehicle is operating in this area. Hence, a deployable/retractable boom mounted loop type antenna is mounted on the forward housing of the IU in the same manner as the existing omni-discone antennas, at an angle of approximately 135° from each. In the deployed state, the antenna extends 40 feet perpendicular to the plane of the solar wings of the ATM. This places the radiating element some 25 feet above the ATM canister, affording excellent coverage in the upper ATM area. Also, coverage is gained in the area immediately to the aft of the CSM, which is a null in the MDA mounted antennas patterns. In the partially deployed state, this antenna can also serve as a backup element in the lower ATM area.

All the antennas used have circularly polarized patterns, which match the polarization of the Teleoperator omni-turnstile antennas. Polarization losses will be kept within a tolerable level with this system.

From the command console, the system operator can select any one of the three major groups of antennas. Where more than one antenna is involved, automatic antenna switching selects the proper antenna on the basis of signal strength. A manual override is available to the operator as a backup.

D.4 SYSTEMS DESIGN CONSIDERATIONS

The Teleoperator is a remote-controlled extension of the man-operator, and requires a large amount of real-time data to be continuously communicated. The particular communications design must fulfill the requirements of a remotely controlled vehicle and must also meet the specific mission requirement of operation around Skylab. During most of its mission life the Teleoperator will be operating at distances of one hundred feet or less from Skylab. This requirement presents problems which affect the ultimate design and must be considered first.

A major problem is avoiding nulls in the antenna radiation patterns, which is solved by correct antenna placement, and is treated in Appendix D.3.

The other problem is multipath destructive signal interference. The magnitude of this problem is not quantitatively known. Multipath interference has been known to cause losses of 20 db (Reference 5.3) within a few feet in cities. Transmitted radio waves being reflected by the surface of Skylab could easily produce this phenomena, seriously degrading the received signal. A reduction in multipath interference is obtained by operation at lower frequencies.

Antenna size and bandwidth efficiency tradeoffs indicate that the VHF band is optimum. At VHF frequencies antenna bandwidths of ten percent are fairly easy to obtain. A Skylab VHF link at 230 MHz dictates that frequencies around 200 MHz be chosen for the RF links.

For bandwidth efficiency reasons an AM modulation scheme was chosen over FM which uses excessive bandwidth. FM, for one percent channels, requires approximately eight times the bandwidth of AM.

Along with the video signals transmitted from the Teleoperator, control signals and feedback signals must be received and transmitted both ways. These consist of thirty-four, fifty Hertz bandwidth signals. A choice of frequency division multiplexing over time division multiplexing was made for the following reasons.

For fifty Hertz bandwidth signals at one percent accuracy sampling rates of 500 Hz are required per channel. If PCM is used an eight bit word would be necessary giving a total bit rate of 136,000 bits per second. PCM gives the advantage of greater accuracy and error correcting techniques, however, the availability of on-board PCM decoders is around 1000 bits per second which is 136 times less than required, eliminating further consideration of PCM.

The availability and proven use of FM subcarrier modulators indicates their use the most advantageous. For a one percent channel a fifty Hertz signal would occupy 875 Hz and for a total of 34 channels plus guardbands the resulting bandwidth is reasonable. Using AM links with FM subcarriers for control signals the total system bandwidth is within allowable limits.

D.5 TELEOPERATOR EQUIPMENT BREAKDOWN

Number	Component	Availability	Volume	Power	Weight
* 70	Voltage Controlled Oscillator	Many Space Flown	0.2 in^3 ea	0.54 W ea	0.15 oz ea
* 2	Mixer Amplifier	Many Space Flown	2.0 in^3 ea	0.61 W	3.0 oz ea
* 2	PAM Commutator	Many Space Flown	9 in^3 ea	3.5 W	12 oz ea
* 2	Baseband Multiplexer	Many Space Flown	40 in^3 ea	1 W	20 oz ea
2	AM Transmitter	Must be specially designed. No problems forseen	40 in^3	10 W	40 oz ea
1	RF (Antenna) Multiplexer	Many Space Flown	261 in^3	Passive	32 oz
* 2	AM Command Receivers	Must be specially designed. No problems forseen	62 in^3 ea	2.5 W	48 oz ea
* 70	Bandpass Filters	Many Space Flown	500 in^3	4 W	110 oz
* 68	FM Subcarrier Demodulator				
	Thruster Logic and Control Circuitry	Must be specially designed. No problems forseen	400 in^3	3.5 W	64 oz
	Priority Logic and Abort Sequencer	Must be specially designed. No problems forseen	500 in^3	4.4 W	80 oz
* 2	Command Decoder	Many Space Flown	20 in^3 ea	5 W	36 oz ea
2	Omni Turnstile Antenna	Many Space Flown	Exterior	Passive	16 oz ea
	Packaging Dead Space		480 in^3		
	Totals		2501 in^3	35.0 W	662.5 oz (41.4 lb)

*Only half of the number shown will be used at any given time.

APPENDIX E
POWER

E.1 POWER COMPUTATIONS

Energy required $= \int_0^{10}$ average power dt

$= \int_0^{1} 165\ dt + \int_1^{9} 195\ dt + \int_9^{10} 165\ dt$

$= 1890$ watt hours

add 10% losses

Energy required = 2100 watt hours

Energy available = Average voltage x Ampere-hrs x 2

= 1.1 x 26 x 70 x 2

= 4004 watt hours

Depth of discharge $= \frac{\text{Energy required}}{\text{Energy available}}$

= 52.5%

Average discharge rate $= \frac{\text{Average power/2}}{\text{Average voltage}}$

$= \frac{210/2}{28.6} = 3.57$ amps

= c/20 rate

E.2 SPECIFICATIONS

Battery Cell Specifications

Nominal capacity	70.0 A-Hrs
Actual output at 7.0 a, 70°F	80.0 A-Hrs
Average voltage at 7.0A, 70°F	1.10 volts
Watt-hours per pound	34.0
Watt-hours per cubic inch	2.7
Recommended Charging Amps	4.0
Recommended Maximum Discharge Amps	70.0
Maximum weight (filled)	4.20 oz
Overall volume (including terminals)	32.1 cu in
Overall height (including terminals)	6.25 in
Width	3.64 in
Depth	1.41 in

Maximum end-of-charge voltage	1.6 volts
Cycle life (75% - 50% discharge)	300-600 cycles
Wet life	3 years
Battery Specifications (each	
Weight	68.3 lbs
Volume	834 cu in
Dimensions	6.25" x 7.28" x 18.3"
Voltage during discharge	27.5 volts
Peak power capacity	2000 watts
Cycle life (60% depth discharge)	450 minimum
Maximum end-of-charge voltage	41.5 volts
Other Specifications	
Regulator unit size (each)	4" x 5" x 6"
Regulator unit volume (total)	240 cu in
Regulator unit weight (total)	10 lbs
Inverter unit size (each)	4" x 4" x 5"
Inverter unit volume (total)	160 cu in
Inverter unit weight (total)	10 lbs
Wiring and Connector weight	10 lbs
Total System Weight	167 lbs
Total System Volume	2068 cu in

E.3 THERMAL ANALYSIS

Battery Heat = (no. cells) x (total current) x (no load voltage - plateau voltage)

= (26) x (7.2) x (1.4 - 1.1)

= 57 watts

Temperature Rise for an Adiabatic Battery

$$\frac{\Delta \text{ Temperature}}{\Delta \text{ Time}} = \frac{\text{Heat}}{\text{Weight} \times C_p}$$

$$= \frac{57 \text{ watts} \times 3.4 \text{ BTU/hr-watt}}{136 \text{ lbs} \times 2.2 \text{ BTU/lb-}^{\circ}\text{F}}$$

$$= .65^{\circ}\text{F/hr}$$

APPENDIX F
THERMAL CONTROL

F.1 SYMBOLS USED

S = Solar Constant = 130 watts/ft^2

A_{p_s} = Average area projected towards the sun = 10 ft^2

A_{p_e} = Average area projected towards the earth = 10 ft^2

A_t = Total Teleoperator surface area = 32 ft^2

R = Average albedo radiation flux constant = 29 watts/ft^2

E = Earth radiation flux constant = 21.9 watts/ft^2

C_p = Specific heat of aluminum = 4.04 watts/min-lb-F

k = Thermal conductivity = 99 BTU/hr-ft-F

W = weight = 634.5 lbs

σ = Steffan-Boltzman Constant = 5.07×10^{-10} watts/ft^2-r^4

Q_{int} = Internal heat; when REMUS is powered up, = 310 watts.
When REMUS is powered down, = 0

α = Absorptance = .4

ϵ = Emittance = .9

$A_{p_{max_s}}$ = Maximum area projected toward the sun = 14 ft^2

$A_{p_{max_e}}$ = Maximum area projected toward the earth = 14 ft^2

R_{max} = Maximum albedo radiation flux = 44 watts/ft^2

$Q_{sun} = A_{p_s} S \alpha$ = 520 watts

$Q_{ref} = A_{p_e} R \alpha$ = 116 watts

$R_{ir} = A_{p_e} E \epsilon$ = 196.2 watts

$Q_{tot} = Q_{sun} + Q_{ref} + Q_{ir} + Q_{int}$ = 832.2 watts powered down
1142.2 watts powered up

$A_{p_{min_e}}$ = Minimum area projected towards the earth = 9 ft^2

X_1 = Percentage of the time REMUS is in sunlight = 64%

X_2 = Percentage of the time REMUS is in reflected sunlight = 50%

For the Camera:

A_{p_s} = 1.34 ft^2

A_{p_e} = .24 ft^2

A_t = 2.37 ft^2

There are three distinct cases we must deal with

1. REMUS is powered up
2. REMUS is powered down
3. ATM film retrieval

F.2 DETERMINATION OF EXTREME TEMPERATURES

F.2.1 Powered Up

The Steffan-Boltzman Equation becomes

$$A_{p_{max_s}} S\alpha + A_{p_{max_e}} R\alpha + A_{p_{max_e}} E\epsilon + Q_{int} = A_t \epsilon \sigma T^4$$

$$(14\ ft^2)(130\ watts/ft^2)(.4) + (14\ ft^2)(44\ watts/ft^2)(.4)$$
$$+ (14\ ft^2)(21.8\ watts/ft^2)(.9) + (310\ watts) = (32\ ft^2)$$
$$(.9)(5.07 \times 10^{-10}\ watts/ft^2\text{-}{}^oR^4)\ T^4$$

$$T = 572\ {}^oR = 112\ {}^oF$$

In a similar manner, the minimum temperature is found by solving the Steffan-Boltzman Equation for the Teleoperator in the earth's shadow.

$$A_{p_{min_e}} E\epsilon + Q_{int} = A_t \epsilon \sigma\ T^4$$

$$(9\ ft^2)(21.8\ watts/ft^2)(.9) + (310\ watts) = (32\ ft^2)(.9)$$
$$(5.07 \times 10^{-10}\ watts/ft^2 - {}^oR^4)\ T^4$$

$$T = 430\ {}^oR = -30\ {}^oF$$

F.2.2 Powered Down

For the powered down mode, we would like to find the amount of power needed by the heaters to keep the Teleoperator at a minimum temperature of 0 ^oF. We can use the Steffan-Boltzman equation and solve for $Q_{heaters}$. The areas used in these calculations are the areas of the Teleoperator when it is docked to Skylab.

$$A_{p_{max_e}} E \epsilon + Q_{heaters} = A_t \epsilon \sigma T^4$$

$$(14\ ft^2)(21.8\ watts/ft^2)(.9) + (Q_{heaters}) = (32\ ft^2)(.9)$$
$$(5.07 \times 10^{-10}\ watts/ft^2 - {}^oR^4)(460\ {}^oR)^4$$

$$Q_{heaters} = 376\ watts$$

The maximum possible temperature will be

$$A_{p_{max_s}} S \alpha + A_{p_{max_e}} R \alpha + A_{p_{max_e}} E \epsilon + Q_{heaters} = A_t \epsilon \sigma T^4$$

$$(14\ ft^2)(130\ watts/ft^2)(.4) + (14\ ft^2)(44\ watts/ft^2)(.4)$$
$$+ (14\ ft^2)(21.8\ watts/ft^2)(.9) + (376\ watts) = (32\ ft^2)$$
$$(.9)(5.07 \times 10^{-10}\ watts/ft^2 - {}^oR^4)\ T^4$$

$$T = 578\ {}^oR = 118\ {}^oF$$

F.2.3 ATM Film Retrieval

When the Teleoperator is doing ATM film retrieval, it will be working in a hot environment. Sunlight reflected from the ATM will be heating the Teleoperator so that almost all of it will be in direct or reflected sunlight. There is, however, no reflected sunlight of infrared radiation from the earth.

$$A_t S \alpha + Q_{int} = A_t \epsilon \sigma T^4$$

$$(32\ ft^2)(130\ watts/ft^2)(.4) + (310\ watts) = (32\ ft^2)(.9)$$
$$(5.07 \times 10^{-10}\ watts/ft^2 - {}^oR^4)\ T^4$$

$$T = 581\ {}^oR = 121\ {}^oF$$

This temperature is near the maximum allowable temperature for some of the subsystems. However, since ATM film retrieval will not take long (30 min max), we will not have to be concerned about this high temperature on most of the Teleoperator because of the large thermal time constant.

F.3 AVERAGE TEMPERATURE OF REMUS (see Figure F. 1)

In actuality, the maximum and minimum temperatures of the Teleoperator will never be reached since the Teleoperator is, during each orbit, heating up and cooling down as it passes from sunlight to shadow. By taking into account the percentage of time spent in sunlight and in shadow, we can find the average temperature (around which its dynamic temperature fluctuates).

F.3.1 Powered Up

$$X_1 A_{p_{max_s}} S \alpha + X_2 A_{p_{max_e}} R \alpha + A_{p_{max_e}} E \epsilon + Q_{int} = A_t \epsilon \sigma T^4_{ave}$$

$$(.64)(14 \text{ ft}^2)(130 \text{ watts/ft}^2)(.4) + (.5)(14 \text{ ft}^2)(44 \text{ watts/ft}^2)$$

$$(.4) + (14 \text{ ft}^2)(21.8 \text{ watts/ft}^2)(.9) + (310 \text{ watts}) = (32 \text{ ft}^2)$$

$$(.9)(5.07 \times 10^{-10} \text{ watts/ft}^2 - {}^{o}R^4)\ T^4$$

$$T = 530\ {}^{o}R = 70\ {}^{o}F$$

This temperature is well within the allowable range for all of the subsystem requirements.

F.3.2 Powered Down

The only difference between the powered up and the powered down modes is the amount of internal heat generated. For the powered down mode, the internal heat generated is 376 watts.

$$T = 540\ {}^{o}F = 80\ {}^{o}F$$

Actually, there is no real reason to keep the Teleoperator at this high temperature when it is not in actual use. A temperature of about 15 - 20^{o}F would be sufficient to satisfy all of the thermal requirements and would need less power. What is recommended therefore, is that the Teleoperator carry

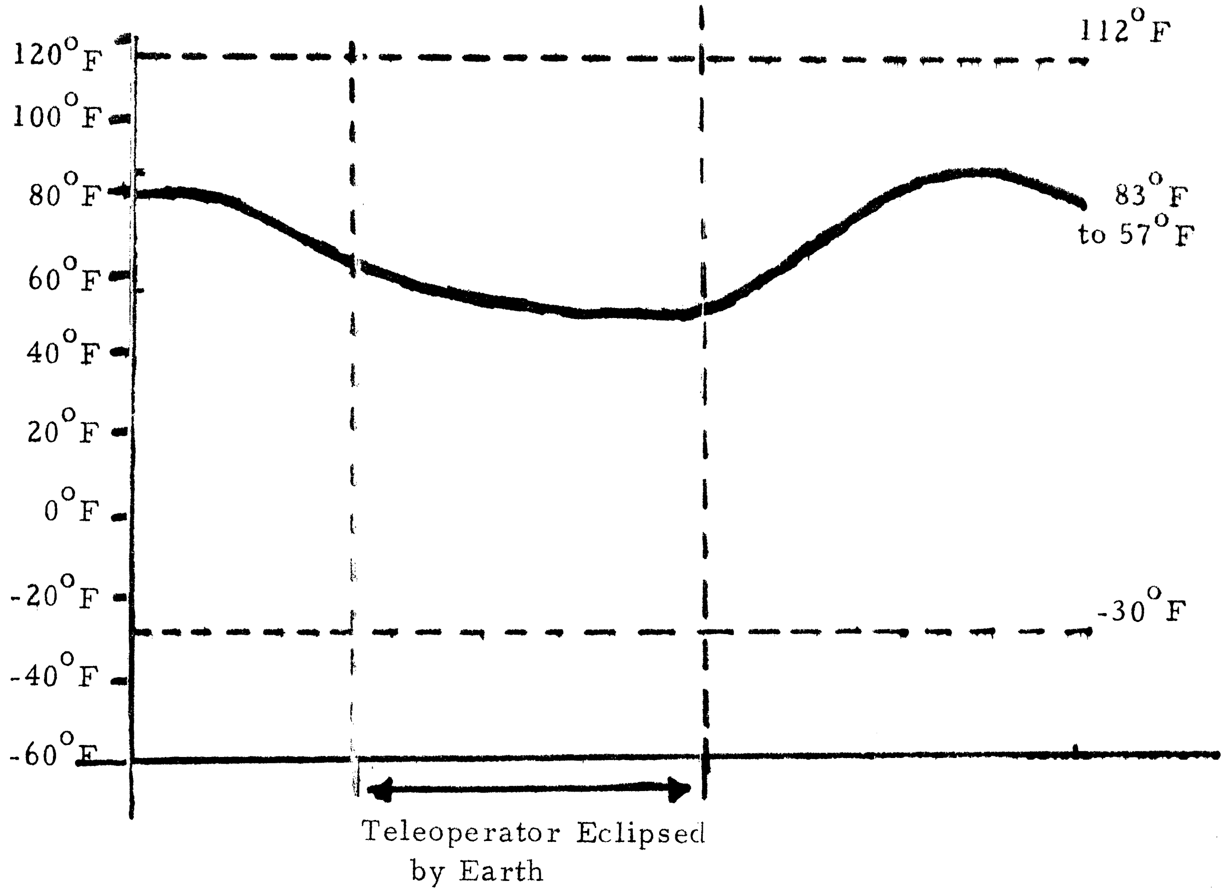


Figure F. 1 Fluctuation of Skin Temperature of Teleoperator Relative to Steady-State
Minimum and Maximum Temperatures of the Teleoperator

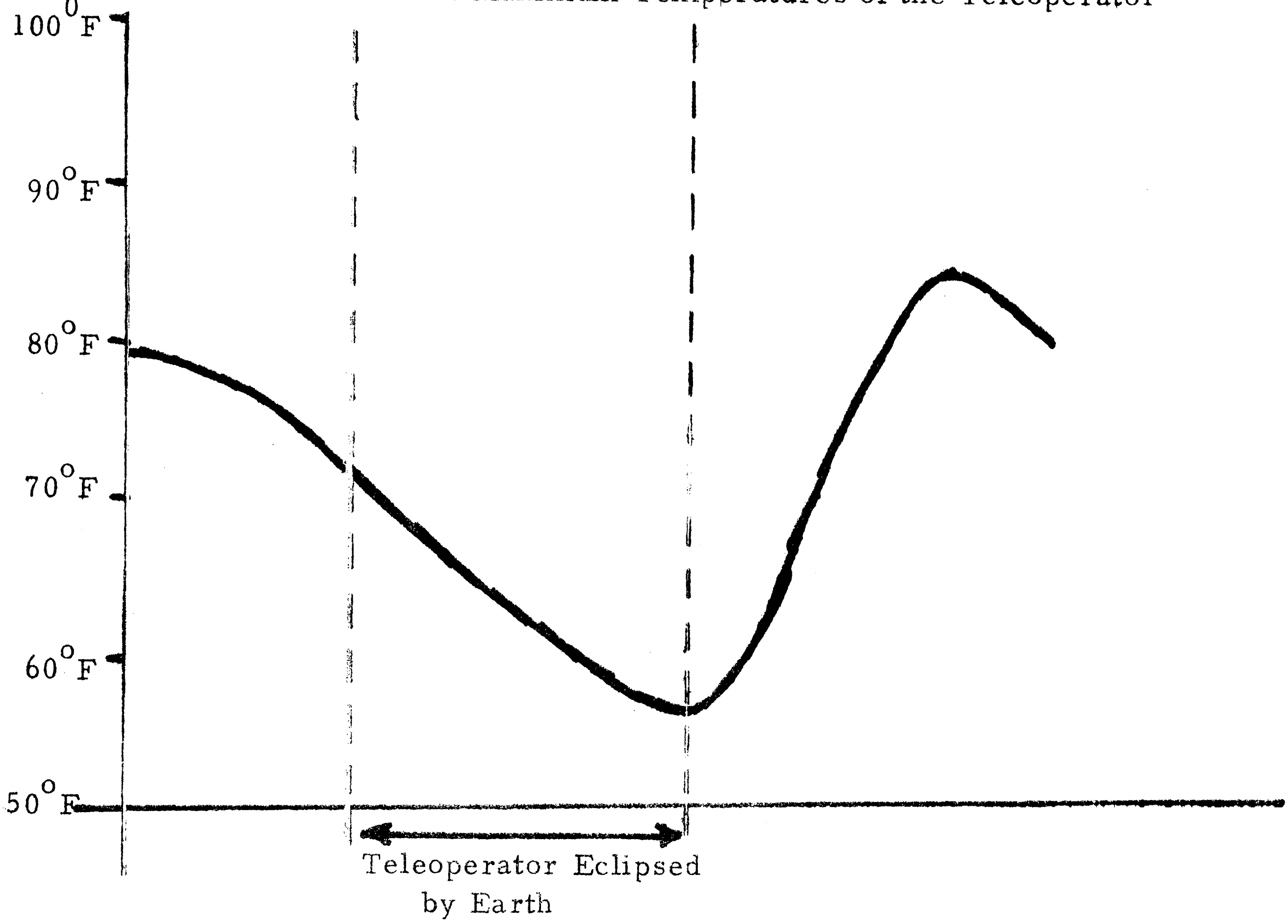


Figure F. 2 Enlarged View of Skin Temperature

376 watts of heaters (their weight is minimal), but the heaters would be turned off when their use is not required. For example, the heaters would be used whenever the temperature in a specific part of the Teleoperator fell below 15 ^{O}F and would be in operation until the part was raised to, say, 30 ^{O}F. They would then be turned off and the part allowed to cool off until 15 ^{O}F is reached again.

Because the Teleoperator has a long thermal time constant (see next section), except for certain components it would take approximately two hours for the entire Teleoperator to drop 15 ^{O}F. This will hold the power requirements from Skylab to a minimum.

F.4 PLACEMENT OF THE HEATERS

The heaters will be located in three main subsections:

1. Cameras
2. Manipulator Arms
3. Flatbed Base

The Steffan-Boltzman Equation can be applied to each of the subsections.

F.4.1 Cameras

All three cameras are identical. (Note: The camera will not face the earth when docked.)

$$X_1 A_{p_{max_s}} S \alpha + X_2 A_{p_{max_e}} R \alpha + A_{p_{max_e}} E \epsilon + Q_{heaters} = A_t \epsilon \sigma T^4_{ave}$$

$$(.64)(1.34\ ft^2)(130\ watts/ft^2)(.4) + (.5)(.24\ ft^2)(29\ watts/ft^2)(.4) + (.24\ ft^2)(21.8\ watts/ft^2)(.9) + Q_{heaters} = (2.37\ ft^2)(.9)(5.07 \times 10^{-10}\ watts/ft^2 - R^4)(540\ R)^4$$

$$Q_{heaters} = 39\ watts/camera \quad 117\ watts\ total$$

F.4.2 Minipulators

Each of the two manipulator arms are identical.

The procedure for finding out the number of heaters necessary is identical with the above procedure. The total area = 5.65 ft^2; the area projected toward the sun = 2.5 ft^2; the area projected toward the earth = 2.0 ft^2.

$$Q_{heaters} = 96 \text{ watts/arm}$$
$$= 192 \text{ watts total}$$

F.4.3 Flatbed Base

For the flatbed base, both the area projected toward the earth and toward the sun is approximately 10 ft^2. The total area is 24 ft^2.

$$Q_{heaters} = 110 \text{ watts.}$$

Note that the 419 watts of heater power found necessary is almost the same as the 376 watts of power found necessary in part 2.B.

F.5 THERMAL TIME CONSTANT

The thermal time constant gives an indication of how fast the Teleoperator will cool off when it enters the earth's shadow. From this thermal time constant, we can find out the approximate temperature fluctuation from our average temperature of 70°F.

$$C_p W \frac{T_2 - T_1}{t_1 - t_2} = A_t \epsilon \sigma T^4$$

Solving, we find out that the thermal time constant is equal to 31°F/hr.

During its time in the earth's shadow, the Teleoperator will cool down approximately 13°F. Also, during its time in the direct sunlight it will heat up about 13°F above its average temperature.

APPENDIX G
STRUCTURES

The following symbols are used in the calculations of Appendix H.

A = area
b = base width
d = outside diameter of tube or cylinder
d_1 = interior diameter of tube
G = rate of material loss to vacuum
h = height
I_{YY} = area moment of inertia
M = molecular weight
$M_{b_{max}}$ = maximum bending moment
p = vapor pressure at temperature T (mm Hg)
s = safety factor
σ_A = total applied stress
σ_{cr} = critical stress
σ_s = maximum shear stress
σ_x = maximum bending stress
T = temperature ^{o}Kelvin
t = thickness
Y = distance to neutral surface

G.1 CAMERA PLATFORM SUPPORT ANALYSIS

The camera platform support is assumed to be a cylindrical cantilever beam with a concentrated end load of 40 lbs. The end load consists of the cameras, camera housing, light and light controls, tilt and pan drives, omni antenna, and upper platform structure. The Saturn V launch subjects the system to a maximum acceleration of 8 G's. The maximum bending moment occurs at the point of attachment to the payload flat-bed.

$$M_{b_{max}} = 320 \text{ lbs} \times 20 \text{ in}$$

$$= 6400 \text{ in-lbs.}$$

The maximum tensile and compressive bending stresses are obtained from

$$\sigma_x = \frac{-M_{b_{max}} Y}{I_{YY}}$$

$Y = 2.5''$

$$I_{YY} = \frac{\pi(d^4 - d_1^4)}{64} \quad \text{and } d_1 = d - 2t$$

d = 5.0" and t = 0.05"

$$I_{YY} = \frac{\pi(625 - 580)}{64} = 2.2 \text{ in}^4$$

$$\sigma_x = \frac{-(6400 \text{ in lbs})(-2.5 \text{ in})}{2.2 \text{ in}^4} = 7300 \text{ psi}$$

The maximum shear stress $\sigma_s = \frac{\text{load}}{\text{area}} = \frac{320 \text{ lbs}}{.785 \text{ in}^2}$

$$\sigma_s = 410 \text{ psi}$$

The total applied stress $\sigma_A = \sigma_x + \sigma_s$

$$\sigma_A = 7710 \text{ psi}$$

The yield stress σ_{cr} for 2014-T6 aluminum of which the camera platform support is constructed is 57,000 psi.

The safety factor is defined as

$$s = \frac{\sigma_{cr}}{\sigma_A} = \frac{57000}{7710} = 7.4$$

G.2 MANIPULATOR ARM SHOULDER SUPPORTS

The shoulder supports are also assumed to be cylindrical cantilever beams supporting a concentrated end weight. Like the camera platform support, the shoulder supports are constructed of 2024-T6 aluminum. With the arms in their folded position the maximum bending moment which occurs at the attachment point to the payload flat-bed is

$$M_{b_{max}} = 440 \times 18 = 7950 \text{ in lbs}$$

The maximum tensile and compressive bending stresses are obtained from

$$\sigma_x = \frac{-M_{b_{max}} Y}{I_{YY}}$$

As before, $I_{YY} = 2.2 \text{ in}^4$

$Y = -2.5 \text{ in}$

$$\sigma_x = \frac{-(7950 \text{ in lbs})(-2.5 \text{ in})}{2.2 \text{ in}^4}$$

$\sigma_x = 9050$ psi

σ_s = maximum shear stress = $\frac{440 \text{ lbs}}{.785 \text{ in}^2}$

$\sigma_s = 560$ psi

For this case $\sigma_A = 9050 + 560 = 9610$ psi

safety factor = s = $\frac{57,000}{9,610} = 5.9$

G.3 SUBSTRUCTURE FRAME ANALYSIS

The vertical support members together with the base substructure bottom frame are also analyzed as cantilever beam assemblies. The support given the structure by the side and frontal coverings is neglected in this analysis.

Because the beams are symmetrical, the maximum tensile bending stresses and maximum compressive bending stresses are equal in magnitude. Therefore, only the compressive analysis will be carried out here.

Compressive stress analysis - starboard vertical support member:
The maximum bending moment occurs at the base end of the vertical support member.

$M_{b_{max}} = 13,286$ in-lbs

during acceleration of 8 G's.

$$\sigma_x = \frac{-M_{b_{max}} Y}{I_{YY}} \qquad Y = 1.0''$$

Here $I_{YY} = \frac{bd^3 - b_1 d_1^{\ 3}}{12}$ = area moment of inertia for a tubular, rectangular beam

$$I_{YY} = \frac{2(2)^3 - (1.6)(1.6)^3}{12} = .786 \text{ in}^4$$

$$\sigma_x = \frac{-(13,286)(-1.0)}{.786} = 16,850 \text{ psi}$$

$$\text{Shear stress} = \frac{\text{load}}{\text{area}} = \frac{710 \text{ lbs x } 8 \text{ G's}}{(2)^2 - (1.6)^2}$$

$$\sigma_s = 3950 \text{ psi}$$

In this case $\sigma_A = 16,850 + 3950$ psi

$$\sigma_A = 20,800 \text{ psi}$$

For 7075-T6 aluminum

$$\sigma_{cr} = 78,000 \text{ psi}$$

$$\text{safety factor} = s = \frac{78,000}{20,800} = 3.75$$

G.4 LAUNCH SECURING MEMBERS ANALYSIS

Because of the Teleoperator launch configuration, the forward and aft launch securing members will be subjected to both normal (compression on starboard side and tension on port side) and shear stresses. The starboard launch securing plate will also receive a portion of the launch loads. The support of the Teleoperator is then distributed equally between five of the six launch securing members: the forward launch securing members and launch bolts, the starboard launch securing plate, and the aft launch securing members.

The load and bending moment at each member is

$$M_{b_{max}} = \frac{5680 \text{ lbs x } 14 \text{ in}}{5 \text{ members}} = \frac{89,520}{5}$$

$$M_{b_{max}} = 17,904 \text{ in-lbs}$$

$$\text{Load at each member} = \frac{5680 \text{ lbs}}{5} = 1136 \text{ lbs}$$

For the launch bolts and forward launch securing members

$$\sigma_s = \frac{\text{load}}{\text{area}} = \frac{1136 \text{ lbs}}{1.72 \text{ in}^2} = 660 \text{ psi}$$

$$\sigma_x = \frac{-M_{b_{max}} Y}{I_{YY}} \qquad Y = -2.5''$$

$$I_{YY} = I_{YY_{\text{launch bolt}}} + I_{YY_{\text{launch member}}}$$

$$= \frac{\pi d^4}{64} + \frac{bh^3}{12} = \frac{(3.14)(.316)}{64} + \frac{8(2)^3}{12}$$

$$= 0.0155 \text{ in}^4 + 5.3 \text{ in}^4 = 5.3155 \text{ in}^4$$

$$\sigma_x = \frac{-(17,904 \text{ in-lbs})(-2.5 \text{ in})}{5.3155 \text{ in}^4} = 8,410 \text{ psi}$$

$$\sigma_A = 8.410 + 660 = 9070 \text{ psi}$$

$$s = \frac{\sigma_{cr}}{\sigma_A} = \frac{75,000}{9,070} = 8.25$$

G.5 RATE OF LOSS OF MATERIAL TO SPACE DUE TO HIGH VACUUM

G = rate of material loss depends directly on surface area A and vapor pressure P

$$G = \sqrt{\frac{M}{T}} \frac{PA}{17.4} \text{ gm/sec}$$

$$G = \sqrt{\frac{26.98}{273}} \frac{(7.24 \times 10^{-8})}{17.4} (25.02 \text{ feet}^2) \frac{9.3 \times 10^2 \text{ cm}^2}{\text{feet}^2}$$

$$G = 2.9 \times 10^{-7} \text{ gm/sec}$$

In one year's time this works out to be:

$$G = 2.9 \times 10^{-7} \text{ gm/sec} \times 3.1536 \times 10^{7} \ \frac{\text{sec}}{\text{year}}$$

$$G = 9.15 \text{ gm/year},$$

a negligible loss

G 6 WEIGHT BUDGET

Video:	Cameras (3)	2.0
	Zoom lenses (3)	10.9
	Control units (3)	13.5
	Lights and light controls (3)	9.0
	Platform	30.0
	Camera enclosures (3)	12.0
	Cabling and switches	6.0
	Total Subsystem Weight	83.4 lbs
Communications:	Internal hardware	39.4
	Omni antennas	2.0
	Total Subsystem Weight	41.4 lbs
Attitude and Control:	Cold gas reaction control system	58.0
	Reaction wheels (3)	30.3
	Rate gyros (3)	4.2
	Rate integrating gyros (3)	3.3
	Automatic control system	1.0
	Total Subsystem Weight	96.8 lbs
Thermal:	Thermocouples	1.0
	Heaters	4.0
	Insulation	1.0
	Total Subsystem Weight	6.0 lbs
Manipulators:	Tether units (3)	40.0
	Arm amplifiers (17)	34.0
	Manipulator arms (2)	110.0
	Total Subsystem Weight	184.0 lbs
Power:	Batteries (2)	136.6
	Regulators (2)	10.0
	Inverters (2)	10.0
	Wiring and connectors	10.0
	Total Subsystem Weight	166.6 lbs
Structures:	Vehicle structural components	133.4 lbs
	Total Vehicle Weight	711.6 lbs
	Weight of Launch Securing System	120.6 lbs
	Total Teleoperator System Weight	832.2 lbs

ACKNOWLEDGEMENTS

Mr. Richard Bernier
Inland Motor Corporation of Virginia
Radford, Virginia

Professor R. M. Berry
Department of Civil Engineering
The University of Michigan
Ann Arbor, Michigan

Prof. Theodore G. Birdsall
Computer Information and Control Engineering
The University of Michigan
Ann Arbor, Michigan

Professor Harm Buning
Department of Aerospace Engineering
The University of Michigan
Ann Arbor, Michigan

Mr. Henry A. Dinter
Honeywell, Inc.
Aerospace Division
Minneapolis, Minnesota

Mr. Donald K. Ekstrom
Matrix Corporation
Huntsville, Alabama

Mr. Carl R. Flatau
Brookhaven National Laboratory
Upton, New York

Mr. Paul Foote
Angenieux Corporation of America
Oceanside, New York

Mr. Allen L. Furfine
McDonnell Douglas Astronautics Company
Saint Louis, Missouri

Mr. G. W. Iler
General Electric Company
Utica, New York

Mr. Alfred Interian
General Electric Company
Valley Forge, Pennsylvania

Mr. John D. Jones
Phoenix Memorial Lab
The University of Michigan
Ann Arbor, Michigan

Dr. Donald Kugath
General Electric Company
Schenecady, New York

Mr. Harold Lanning
Bendix Company
Aerospace Systems Division
Ann Arbor, Michigan

Mr. Tom Loren
Ball Brothers Research
Aerospace Division
Boulder, Colorado

Prof. John A. M. Lyon
Department of Electrical Engineering
The University of Michigan
Ann Arbor, Michigan

Mr. Kenneth M. Mallory, Jr.
Matrix Corporation
Huntsville, Alabama

Professor E. Lawrence McMahon
Department of Electrical Engineering
The University of Michigan
Ann Arbor, Michigan

Mr. Ernest J. Merz
Valley Forge Space Technology Center, General Electric Co.
Philadelphia, Pennsylvania

Mr. Donald P. Mingesz
Argonne Laboratory
Argonne, Illinois

Professor William F. Powers
Department of Aerospace Engineering
The University of Michigan
Ann Arbor, Michigan

Mr. Hal F. Schulte
College of Engineering
The University of Michigan
Ann Arbor, Michigan

Mr. Richard J. Simms
The Bendix Corporation
Aerospace Systems Division
Ann Arbor, Michigan

Mr. E. L. Svensson
Westinghouse Electric Corporation
Baltimore, Maryland

Mr. Kirby Thomas
Martin Marietta Corporation
Denver Division
Denver, Colorado

Mr. Peter D. Valianos
General Electric Company
Space Systems
Philadelphia, Pennsylvania

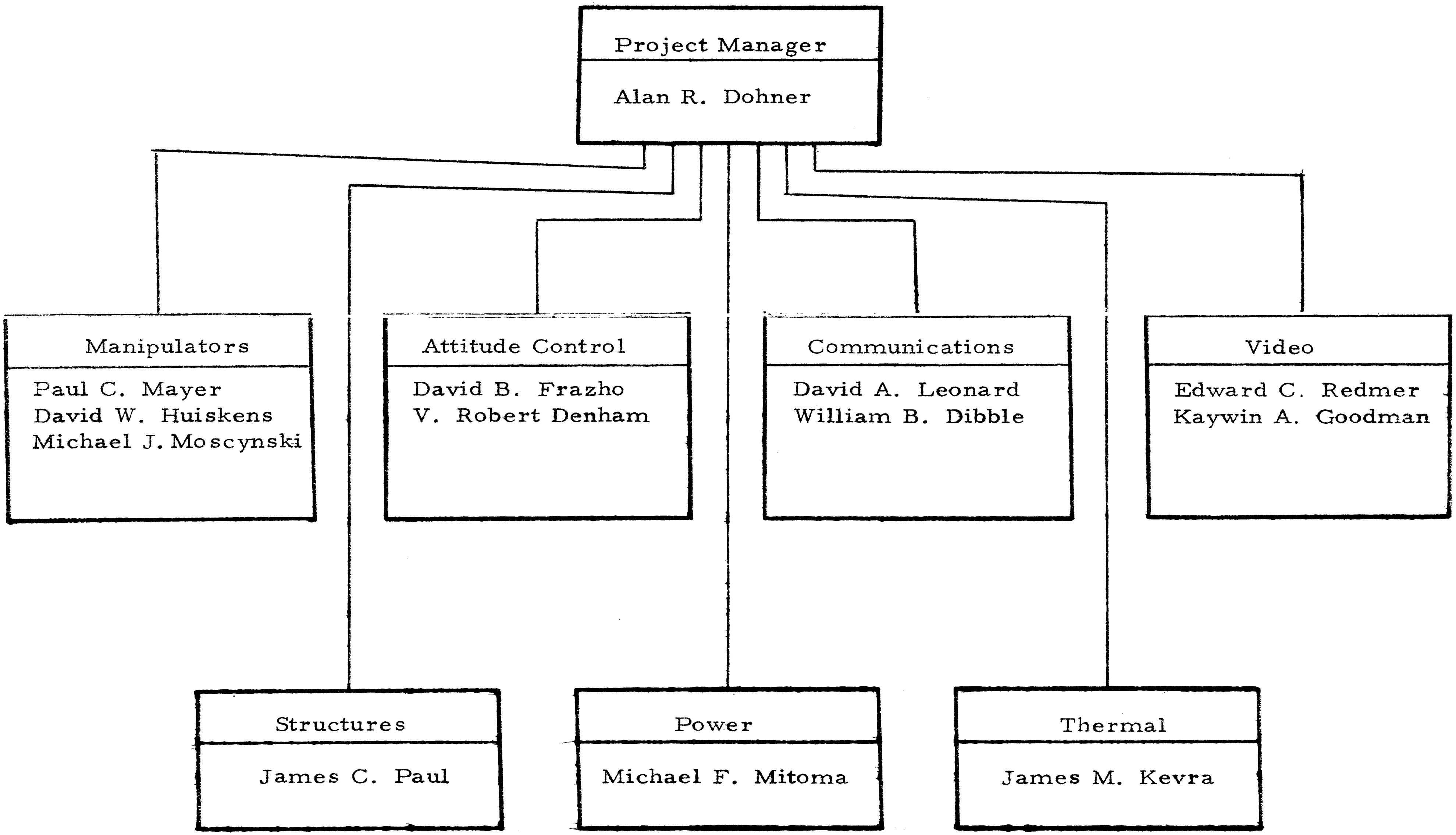
Mr. J. F. Walker
SPAR Aerospace Products, Ltd.
Toronto, Canada

Mr. H. R. Warren
SPAR Aerospace Products, Ltd.
Toronto, Canada

Mr. Floyd H. Weir
U.S.M. Corp.
Gear Systems Division
Birmingham, Michigan

Professor W. J. Williams
Department of Electrical Engineering
The University of Michigan
Ann Arbor, Michigan

We would like to say a special word of appreciation to Professor Wilbur C. Nelson for his guidance throughout Project REMUS and also to Caroline Rehberg for typing our report. Also to Sam Nakamura for his assistance this term.



Project Personnel Chart