ME 4182
MECHANICAL DESIGN ENGINEERING

NASA/UNIVERSITY
ADVAVCED DESIGN PROBLEM

# LUNAR ROBOTIC MAINTENANCE MODULE

DECEMBER 1988

MICHAEL L. AYRES

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Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

**Georgia Institute of Technology**
Atlanta, Georgia 30332-0405

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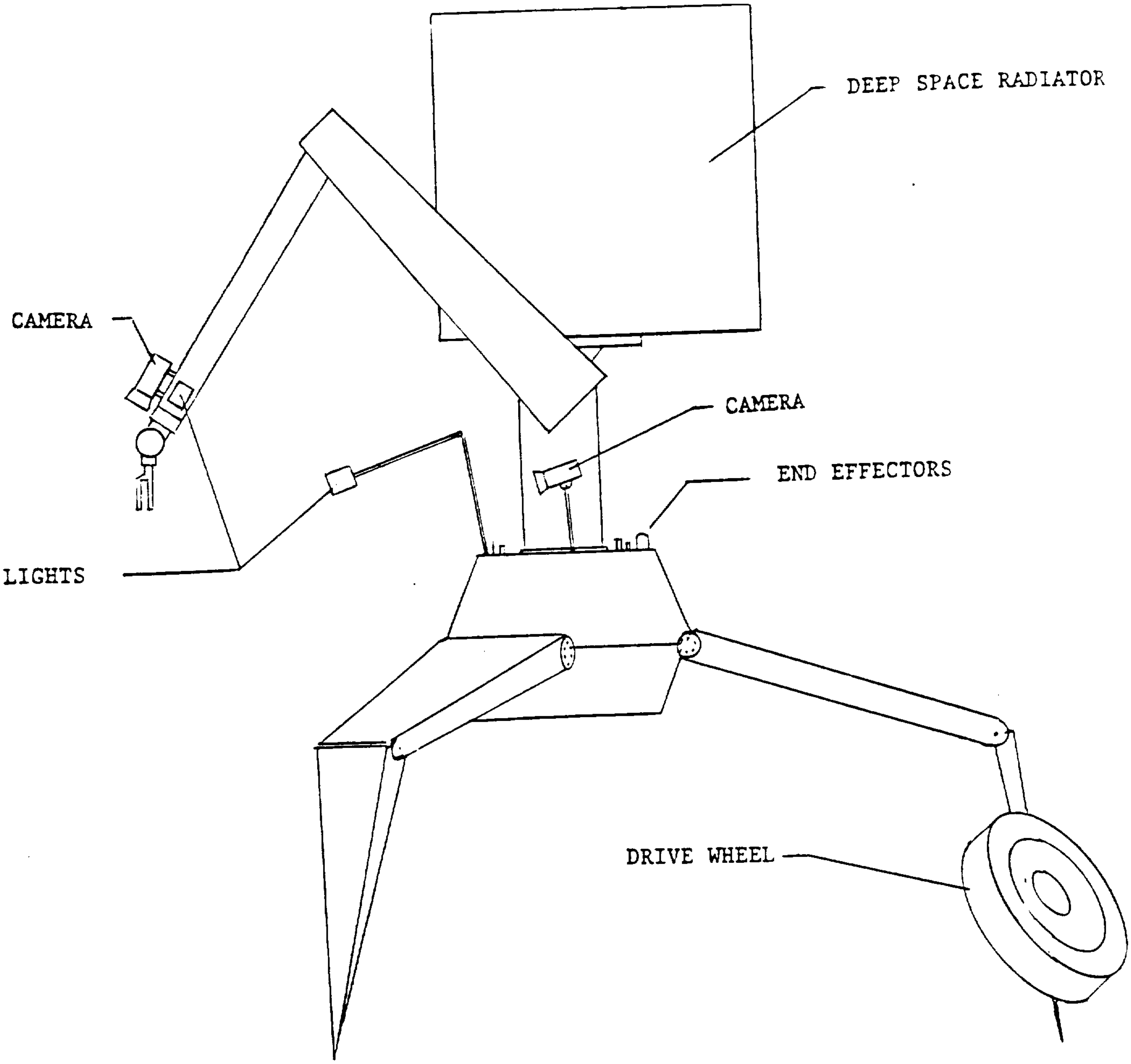

ROBOTIC MAINTENANCE MODULE

FIGURE 1

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# 1. Abstract

The objective of this report is to introduce a design for a robotic maintenance module that will assist a mobile 100-Meter lunar drill. The design considers the following areas of interest; the atmospheric conditions, actuator systems, power supply, material selection, weight, cooling system and operation.

## 2. PROBLEM STATEMENT

BACKGROUND: In the near future , NASA is planning to explore the moon in greater detail. This includes the use of machines such as a mobile 100-Meter lunar drills to drill into the lunar surface to depths up to 100 meters. This depth is ideal for taking core samples, placing explosives under the surface or research instruments. A robotic module is required to assist the lunar drill in its operations and to perform maintenance tasks to ensure continued operation of the lunar drill.

PERFORMANCE OBJECTIVES:

1. Load and unload the 2-meter length drill string as required for drilling.
2. Be able to take core samples from the lunar drill and store in a suitable place.
3. Be able to accompany a mobile lunar drill anywhere it might go.
4. Remote operation
5. Replace drill bit when necessary
6. Perform routine and unscheduled maintenance tasks when required.

CONSTRAINTS:

1. Lunar environment:
    - A. Extreme thermal conditions (-170 C to 130 C)
    - B. Vacuum does not allow convective heat transfer, sound pressure or oxidation to occur.
    - C. Gravity is one-sixth of the Earths.
    - D. High levels of solar radiation.
    - E. High levels of particulates near drill site.
2. Low Weight to reduce launching costs.

# 3. DESCRIPTION

Based on the information I have gathered about the lunar environment and the tasks which the design must be able to perform, I have analyzed and created a design for a robotic maintenance module which will meet the requirements of the design. My main concerns involve the modules operation in the lunar environment, earth to moon transportation costs and life expectancy.

As with many mechanical systems, the robotic maintenance module is a system which consists of many subsystems. The result is a robotic tripodal base similar to the Skitter design that will give the module the ability to move completely around and on top of the mobile lunar drill. A six degree of freedom robotic arm is mounted atop the tripodal base to carry out tasks required for lunar drilling and can act as a fourth leg for the module to move about on. See figure 4. A motor driven wheel will be mounted on two of the tripodal bases legs with an attachment for towing mounted on the remaining leg. This setup will allow the module to follow the mobile lunar drill by towing without creating a traction problem associated to the increased load of towing another vehicle. See figure 1.The drive wheels will be constructed of an aluminum alloy for light weight and they will have a chevron design tread for maximum traction.

The base will consist of a sealed compartment that will be pressurized to house the microprocessors and communications equipment essential to the operation of the module. The gas in this compartment will be transported though pipes to all the electric motors in the module by blowers and cooled via a deep space radiator. Due to the environment of the moon there exists the condition suitable for high thermal emissivity that allows for effective radiant cooling. See figure 2.

The primary task of the module is to make sure that the mobile lunar drill is operating properly. To accomplish this task the module will load and unload the drill string extensions as required for drilling. The module will replace worn drill bits either by controller examination or at timed intervals. The module will retrieve core samples from the drill string and place them in separate containers. The module will perform routine and unscheduled maintenance to the lunar drill such as solid lubrication for critical wear areas or areas that receive a lot of dust.

The module will be preprogrammed for the task of assisting the lunar drill. The microprocessors will be designed in such a way to allow reprogramming for other maintenance tasks that might be required on the moon. This is especially desirable because the module is designed to acomplish many different tasks besides that required for lunar drilling and cuold be very helpful in fixing other broken machinery on the moon.

The power supply of the module will be a rechargable battery that is carried in the bottom of the module base to aid in stability while the robotic arm is handling objects. The charge life of the battery is to be approximately twenty-four hours which will allow the module to assist in about ten 100-meter borings before a recharge is necessary. See figure 2 and figure 5.

The module will carry several different end effectors for the robotic arm. There will be an end effector for picking up the drill string extensions, one for installing the drill bit to the drill string, one for providing solid lubricants to areas requiring this, one for positioning the video cameras and lights, and possibly more for other tasks in the future. These end effectors will be placed at the base of the robotic arm for easy retreival. See figure 3.

The module will carry two video cameras with one mounted on the robotic arm and one mounted on the base itself. These cameras will provide the controller with a view to what is taking place on the moon. Two lights will also be mounted on the module by movable arms so that the robotic arm may position them for the best lighting. Since Lighting on the moon is either fully bright or totally dark it is necessary to have auxillary lighting to enhance vision. Due to this phenomena, maintenance would ideally be performed during the lunar night or possibly in the shadoe of a crater.

The module will carry essential spare parts for the lunar drill such as the drill bits and solid lubrication. The module will also be capable of transporting some of the drill string extensions which will enable the robotic arm to pick up a heavier load due to the increase in the normal force.

# 4. ANALYSIS

INTRODUCTION: The lunar environment and the weight of a design are the two most constraining limitations that must be considered for lunar operating system to be functional. The extreme conditions on the moon demand a material that has a low thermal expansion to avoid thermal stresses caused by the high temperature gradients of 130 C in the light to -170 C in the shade. Problems arise for cooling of the electric motors and circuits when the module is operating in the day.

There is virtually no atmosphere on the moon which results in a vacuum like that encountered in deep space. The vacuum on the moon does not allow convective heat transfer to occur or for sound to travel because there is no median for propagation. The vacuum does not allow oxidation to occur but there are high levels of solar radiation which prohibits the use of rubber or thermoplastics unless they are shielded. The vacuum prohibits the use of any wet lubricants because they would quickly evaporate and therefore solid lubricants most be used.

The gravity on the moon is approximately one-sixth that of the Earths which means that a machine cannot rely on normal forces to maintain stability. Furthermore, the mass of the machine cannot be increased to recover stability due to the high expense of space transportation.

## 4.2 STRUCTURAL SUPPORT

200

**WEIGHT:** A robotic tripodal base, robotic arm, microprocessors, battery and associated components make up the robotic maintenance module. The total weight of the entire system is approximately xxx pounds. The robotic tripodal base must be designed to support this weight and the additional forces that the robotic arm will create.

**LEVELING ALIGNMENT:** The robotic tripodal base will provide the gross module movement around or on the mobile lunar drill. THe lunar drill will have something so that the microprocessor determine the position of the module relative to the lunar drill. Using this information the robotic arm may proceed with its assigned task.

## 4.3 POWER SUPPLY

1. ROBOTIC TRIPODAL BASE: The tripodal base requires two DC servo motors in each leg for a total of six motors. These motors will only need to be operated when the module arrives at a drill site and unhitches from the mobile lunar drill to get in position to assist the drilling operations. If maintenance is required then the module might have to reposition itself relative to the lunar drill. Upon completion of the drilling procedure the module must walk to the back of the lunar drill and hitch up.

2. ROBOTIC ARM: The robotic arm requires six DC servo motors to accommodate the six degrees of freedom. These motors will only need to be operated when the arm has a task to carry out. The robotic arm will have a microprocessor in its base to control the movements required for its assignments.

3. DRIVE SYSTEM: Two DC motors will drive the module while it is being towed behind the mobile lunar drill to the designated drill site. These motors will operate continuously while the vehicles are in motion and will require a total of five horsepower to reach a maximum speed of ten miles per hour.

4. COMMUNICATIONS: The module will have one or two video cameras and two lights so that video communications from earth are possible with a transmitter and receiver.

5. COOLING SYSTEM: A pressurized gas will be the working fluid of the cooling system and will be circulated by blowers as shown in figure xx.

5. PRESSURIZATION: The interior of the module will contain a sealed and pressurized compartment to aid in absorption of heat created by the motors and electronic components

## 4.4 MATERIALS

Material Selection: The material selection of the robotic maintenance module must be of low mass, high strength, minimum radiation effect, low thermal expansion. The low mass requirement is the most important factor in the material selection because the current cost to launch space vehicles is approximately $10,000 per pound. Therefore, aluminum alloys were considered feasible. Due to its relatively low density, .09 lb/cu in, 6061-T6 aluminum was chosen. The T6 heat treatment gibes the alloy an average strength of 55ksi. The 6061-T6 aluminum alloy meets the low thermal expansion requirement necessary for the extreme temperature gradients encountered on the moon.

## 4.5 CONTROL SYSTEMS

SENSOR SUBSYSTEM: The module will have several modes of sensing equipment for vision, position, velocity and acceleration. The vision sensor system is made up of two video cameras, one mounted to the end of the robotic arm and the other mounted on the base of the module as shown in figure xx (Appendix xx). Two lights will be used on the module to enhance the video image that the operator is viewing. Maintenance tasks will be performed in the shade or during the lunar night whenever possible to aid the controllers visual image. The cameras and lights will be positioned by robotic arm. The position sensor system will enable the module to determine its position relative to the lunar drill and thus be able to complete a task without controller input such as loading the lunar drill with a drill string extension. The velocity/accelerometers will give the microprocessors feedback while performing tasks.

COMPUTER SUBSYSTEM: The module will contain two on-board microprocessors that will be networked together to share information and tasks. One of the microprocessors will be housed in the base of the robotic arm as shown in figure xx. It will control the movement and operation of the robotic arm and the functions of the cameras and lights. The other microprocessor will control the movement of the tripodal base, the cooling system, the drive wheels and the communications for remote operation.

## 4.6 COOLING SYSTEM

The base of the robotic maintenance module will contain a sealed compartment that will be pressurized with a gas to allow convective heat transfer. The microprocessors and communications equipment will be housed inside of the pressurized compartment which will be maintained at a specified temperature. The electric motors in the robotic arm and legs will be in sealed compartments connected to the base compartment by piping as shown in figure 6. Circulating fans will transport this heated gas to a deep space radiator that the robotic arm has positioned facing deep space. This sealed compartment will be separated from the outside casing of the module by a ceramic composite that has low thermal conductivity and high fracture toughness to avoid failure by shock or vibration. The drive motors for the wheels will produce the most amount of heat for a given time when the module is being towed by the lunar drill because they must operate continuously. The heat generated in these motors is produced by electro-mechanical losses in the motors themselves, friction in the bearings and friction in the gear interfaces. This heat must be dissipated to avoid motor failure. The cooling system will bring a cooled fluid from the deep space radiator to each sealed motor compartment by blowers and will carry the excess heat back to the radiator. Thermocouples will be placed in each sealed compartment to allow the microprocessor to monitor the temperatures and adjust the mass flow of the fluid to maintain a specific temperature within the module. See figure 7.

## 4.7 OPERATION

The robotic maintenance module operation process is a computerized robotic system and the main duty of the controller is to monitor the operation of the module. The controller will have a scaled down version of the module on earth which by manipulating the earth module the lunar module will follow these actions. This will give the controller a better feel for what the module is doing. Otherwise the operation of the module wil be controlled by the microprocessors on-board in the following steps.

1. Follow the mobile lunar drill to the specified drill site ia a modified tow.
2. Unhitch from the lunar drill and extend legs to allow movement to a position in such a way so that the robotic arm may load the drill string.
3. Attach the drill dit to the first part of the drill string.
4. Load drill string extensions as required for desired depth.
5. Collect core samples and place in containers identifying the depth and bore number.
6. Unload the drill string extensions when drill string is being removed from the bore.
7. Hitch back up to the lunar drill and contract legs so that the drive wheels of the module will contribute to the motion of the vehicles to the next drill site.

## 4.8 FAILURE

The robotic maintenance module is a very complicated system with many electronics and controlls. The heart of the module is located in the pressurized base where the microprocessor and communication systems are contained. The operation of these systems requires that the cooling system is functioning properly and the pressurization of the fluid is maintained. If the cooling system fails or the pressurization is lost the electronics will soon burn up if the module is operating during the lunar day. These systems must therefore be designed for high reliability to ensure that the module will be able to carry out the tasks it is assigned.

## 5. RECOMMENDATIONS

The robotic maintenance module proved to be a very challenging project because of the special application to the moon and the wide variety of tasks that the module must perform. The design had to be automated and special attention had to be given to the cooling system and power supply. Many details including the subsurface conditions are unknown about the moon and substantial error may be involved with this design. It is recommended that a prototype model be built and tested in a simulated lunar environment in order to see how all the systems work together as a whole. This testing will provide information about the performance of the module in its ability to carry out tasks. Elapsed time figures for actual tasks could be compared with calculated estimates to see how practical the operation really is. Telecommunication of commands for the prototype would enable designers to see how well the module actually works in the real world. Fatigue analysis should be carried out on all the highly stressed components to determine their reliability which is critical for a design of this type. It is recommended that the complete structure of the module undergo finite element analysis to minimize the mass and retain high reliability because this will substantially reduce the launching costs of the module thereby making it more a more feasible design.

## 6. REFERENCES

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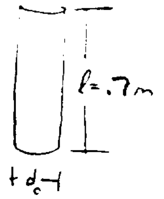
[illegible] OF MODULE

ARM 1



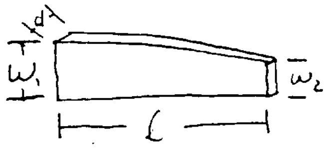
$\ell = 1.2$m   $d_o = 0.25$m   $t = 0.005$m   $\rho = 2770$ kg/m$^3$

$$m = \frac{\pi \ell \rho}{4}\left(d_o^2 - d_i^2\right) = \frac{\pi(.7)(2770)}{4}(.25^2 - .24^2)$$

$m = 7.45$ kg

ARM 2

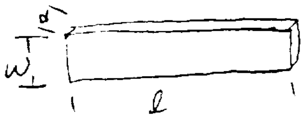
$\ell = 1.5$m   $w_1 = 0.25$m   $w_2 = 0.1$m   $d = 0.125$m   $t = 0.005$m
$\rho = 2770$ kg/m$^3$   $\ell = 13$ m



$m \approx (2w_1 + 2d)\ell t \rho = 13.6$ kg

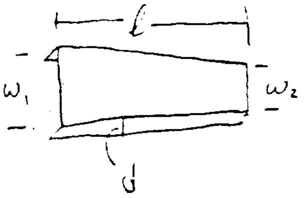
ARM 3

$w = 0.1$m   $\ell = 1.2$m   $d = 0.1$m   $t = 0.005$m   $\rho = 2770$ kg/m$^3$



$m \approx (2w + 2d)\ell t \rho = 6.65$ kg

leg 1



$\ell = 1.2$m   $w_1 = .4375$m   $w_2 = .25$m   $d = .1$m
$t = 0.005$m   $\rho = 2770$ kg/m$^3$

$m \approx (w + 2d)\ell t \rho = 9.3$ kg

$m = 9.3 - 2.7 = 6.6$ kg

leg 2

$\ell = 1.0$m   $w = .2$m   $d = .1$m   $t = .005$m

$m = 3.65$ kg

# APPENDIX A

Calculations for heat generation by electric motors and electronics

1. Heat dissapated for drive motors

   Assume 90% efficiency for all motors

   Heat loss = $\dot{Q} = \frac{P_{out}}{\eta} - P_{out}$

   $P_{out} = 5$ H.P. $= 3730$ Watts

   $\dot{Q} = \frac{3730}{0.9} - 3730 \simeq 414$ watts

2. Heat dissapated for tripodal base motors

   Assume total output for all six motors to be approximately 6 H.P.

   $P_{out} = 6$ H.P. $= 4476$ watts

   $\dot{Q} = \frac{4476}{0.9} - 4476 = 497$ watts

3. Heat dissapated by robotic arm motors

   Assume total output of all six motors to be 3 H.P.

   $P_{out} = 3$ H.P. $= 2238$ watts

   $\dot{Q} = \frac{2238}{0.9} - 2238 = 249$ watts

4. Heat dissapated by two microprocessors and communication system.

   Assume $\dot{Q} = 200$ watts

Since the motors in the tripodal base and robotic arm will not be operated continuously, their heat dissapation is negligable in the design of the cooling system. Therefore the cooling system will be based upon the heat dissapation of the drive motors and electronics.

# APPENDIX A

A cooling fluid will be provided to each sealed compartment for the drive motors. This fluid will be driven by fans located in each sealed compartment.

$\dot{Q} = \sigma A_s T^4$ $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$

$A_s$ = surface area of radiator, $m^2$

T = absolute temperature of radiating surface, °K

$\dot{Q}$ = heat dissaporated, Watts

Assume radiation occurs mainly at 315 °K

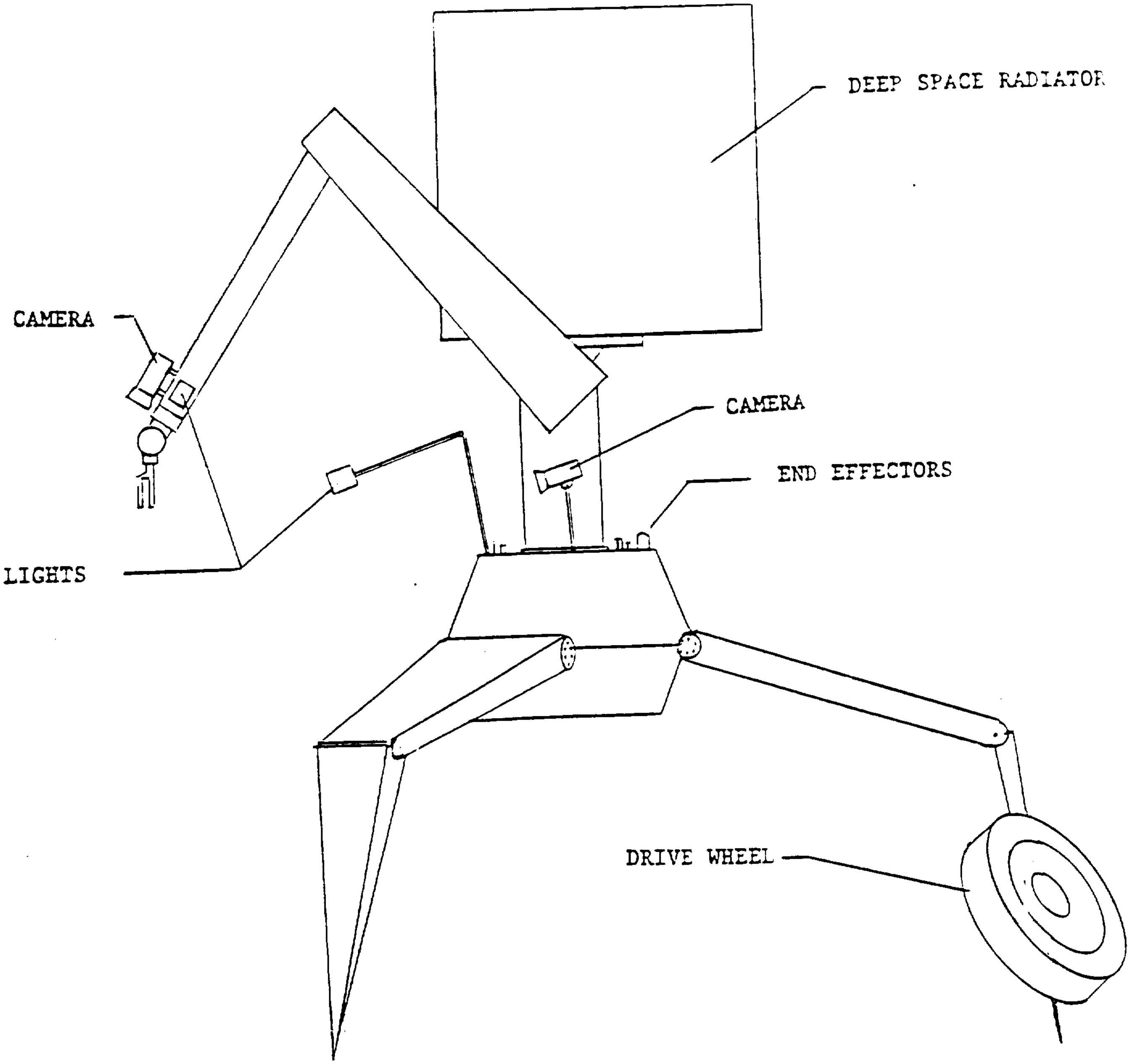
$\dot{Q}_{motors} = 414$ watts

$\dot{Q}_{electronics} = 200$ Watts

$$A_s = \frac{\dot{Q}_m + \dot{Q}_e}{\sigma T^4} = \frac{614 \text{ Watts}}{(5.67 \times 10^{-8} \frac{W}{m^2 K^4})(315K)^4} = 1.099 \, m^2$$

Therefore radiator should be 1.1 square meters

# APPENDIX B: DRAWINGS



ROBOTIC MAINTENANCE MODULE

FIGURE 1

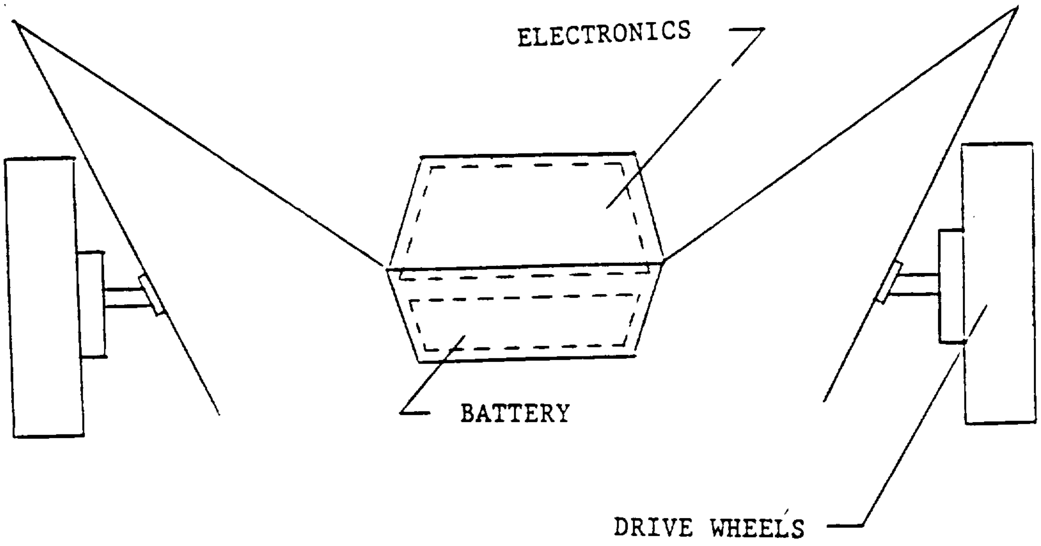
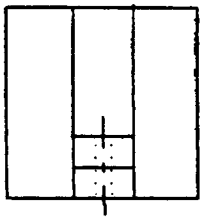
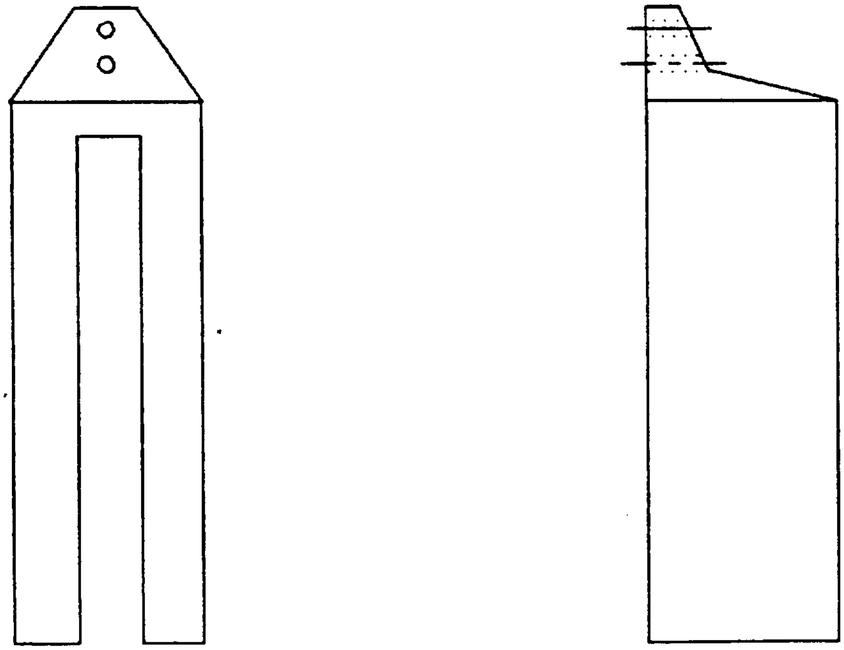


FIGURE 2



FRONT VIEW

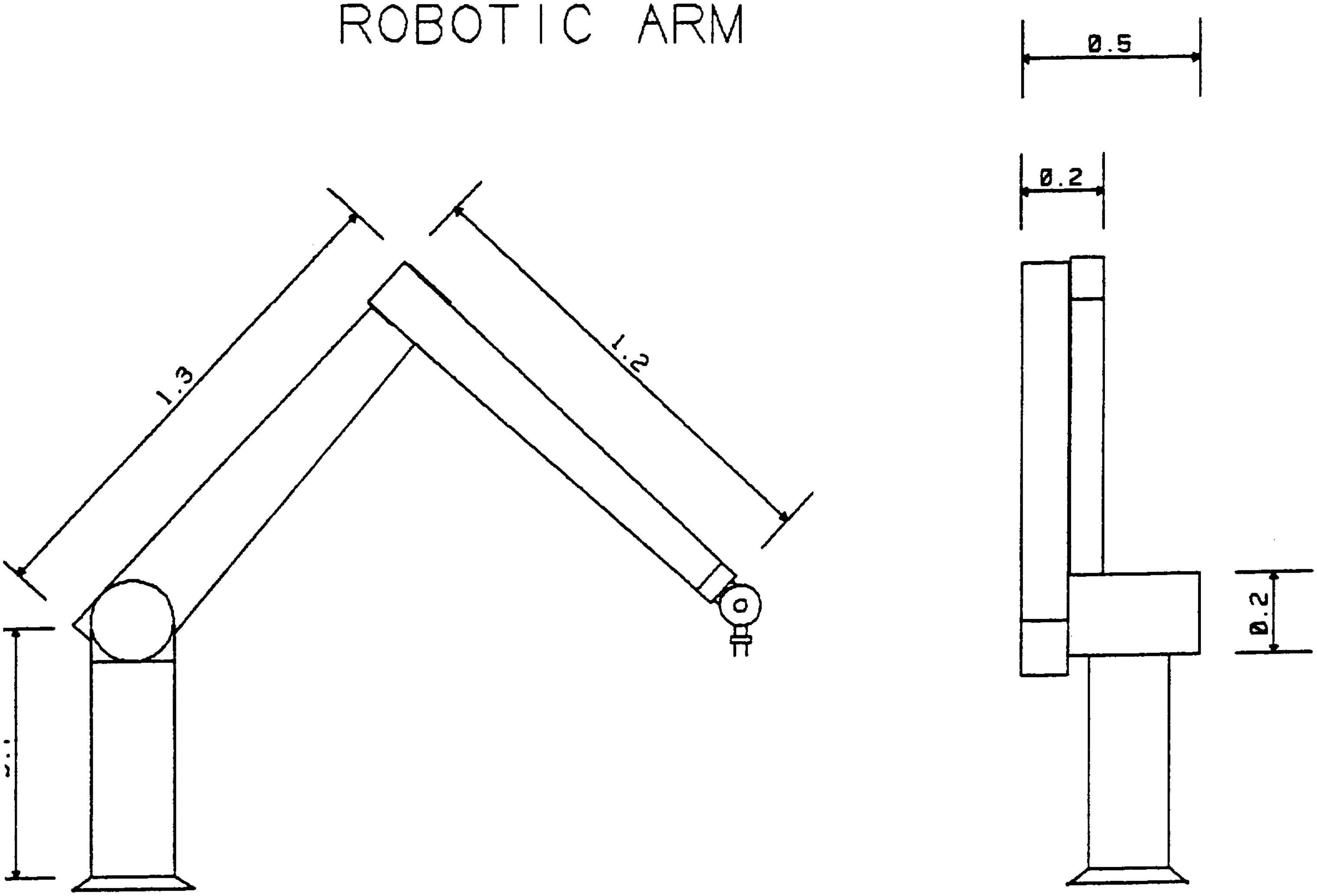


SIDE VIEW TOP VIEW

END EFFECTOR FOR ROBOTIC ARM

FIGURE 3

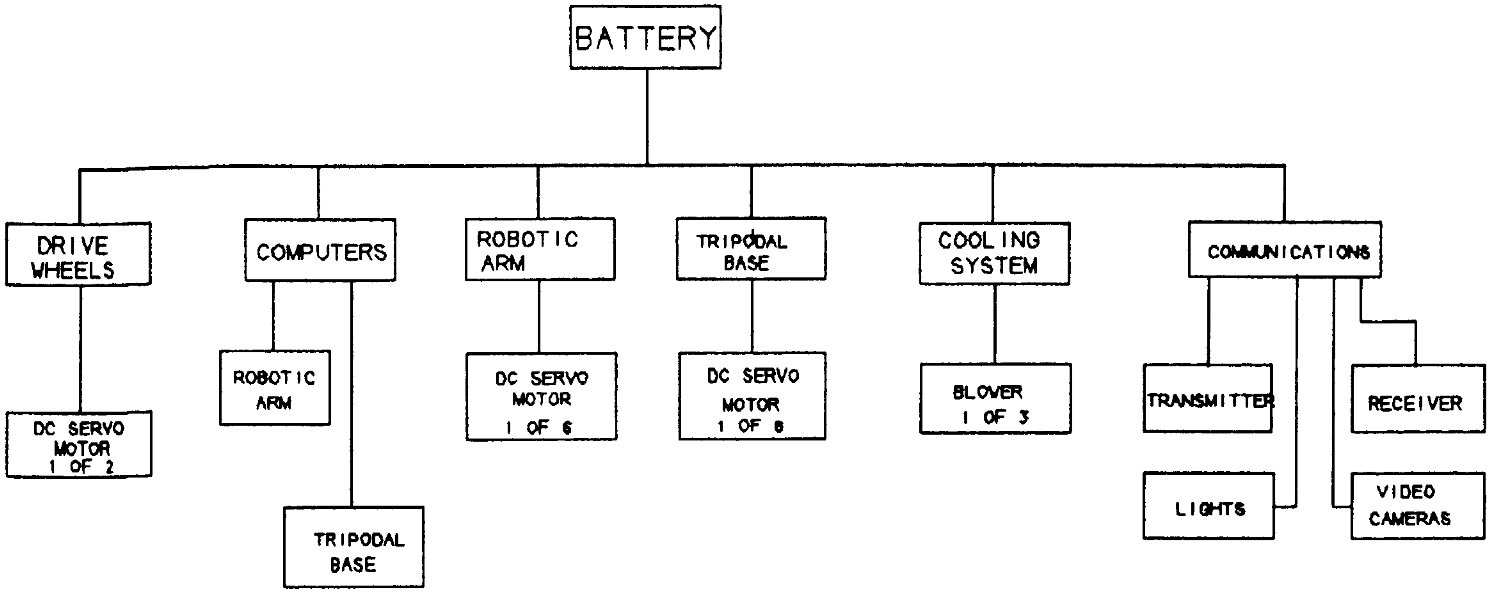
# SIX DEGREE OF FREEDOM ROBOTIC ARM



FRONT VIEW

SIDE VIEW

FIGURE 4



POWER REQUIREMENTS FOR THE ROBOTIC MAINTENANCE MODULE

FIGURE 5

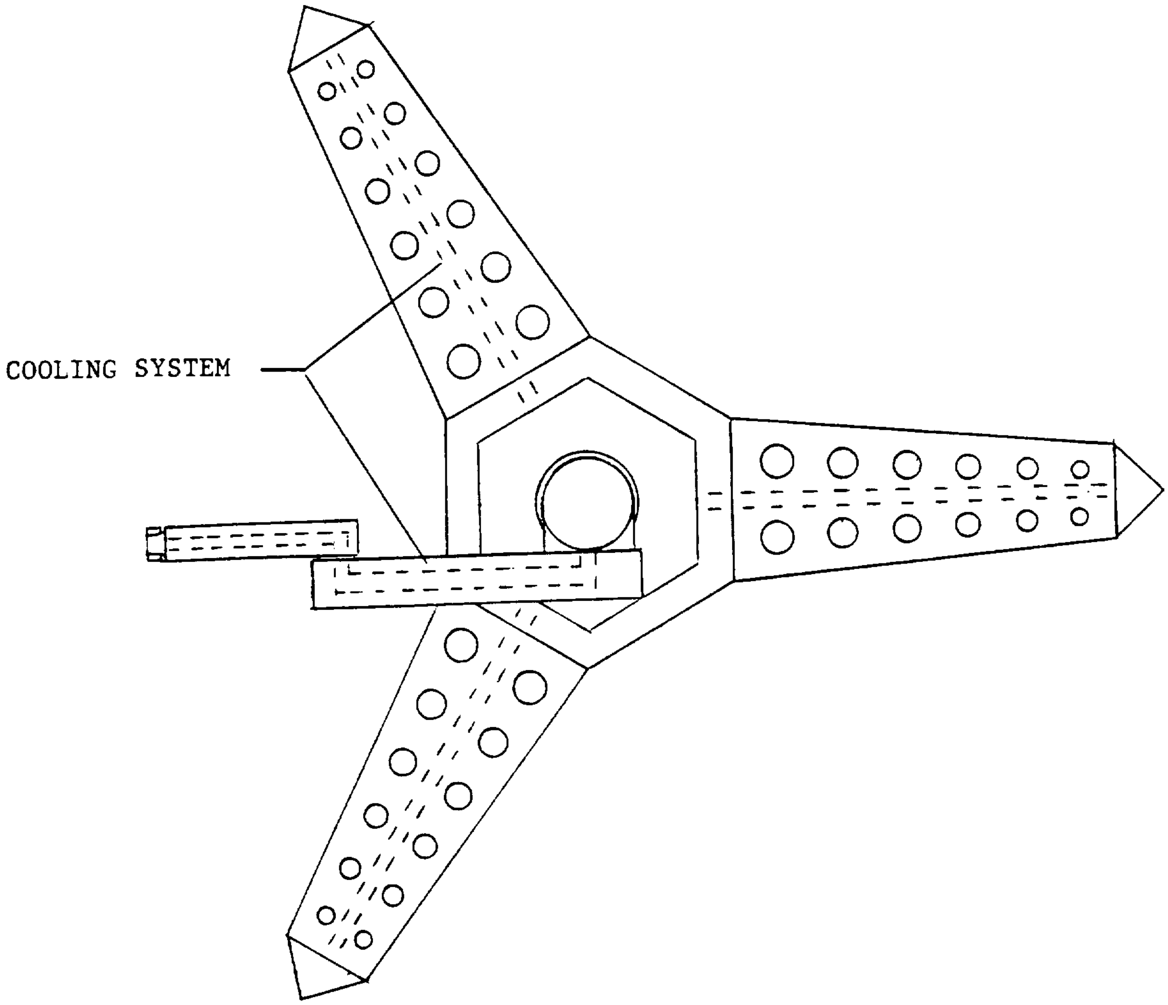
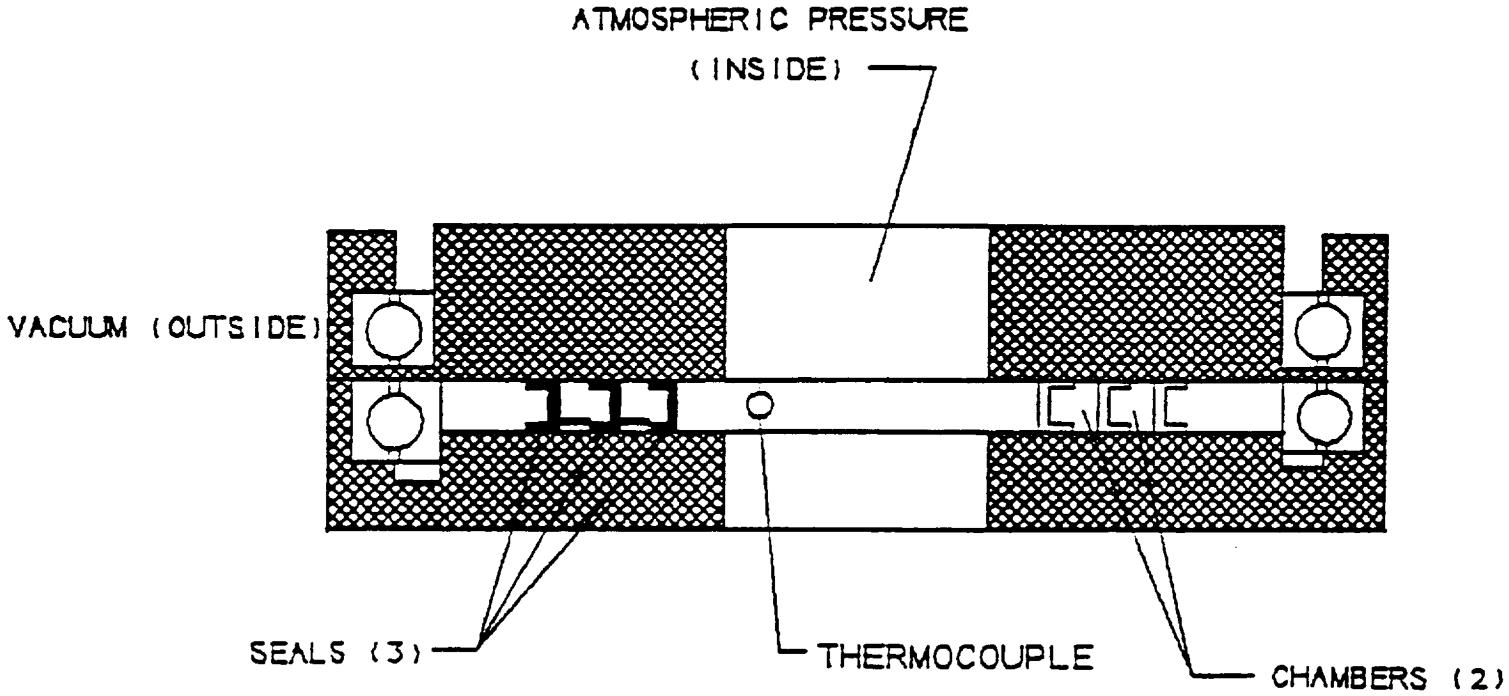


FIGURE 6



80% TEFLON AND 20% GRAPHITE SEALS

DIFFERENTIALLY PUMPED SEALS

360 DEGREE ROTATION

ROTARY SEAL FOR ROBOTIC ARM

FIGURE 7

# MECHANICAL DESIGN ENGINEERING

## ME 4182

PROJECT TITLE: Robotic Maintenance Module
DATE: 11 Oct 1988
SUBJECT: Progress Report

The problem statement for the robotic maintenance module has been drafted and revised. The module is to be designed as a tool to assist and maintain operation of rover and skitter drilling rigs in the lunar environment. The tasks of the module are to include loading and unloading of drilling extensions and drilling bits during the drilling process, repair of broken or malfunctioning components of the drilling rigs and supply expendibles such as lubricant when necessary.

The module must be able to perform in the lunar environment and be pre-programmed for its tasks because communication is limited to line of sight. This will require an onboard computer which can be loaded with the information required to assist and maintain operation of the drilling rigs. The module must also carry enough drilling extensions to enable successful operations.

The module will be based on a design similar to that of the skitter. There will be three legs which will enable the module to follow the drilling rig to which it is assigned. There will be two robotic arms used for retrieval and placement of the drilling extensions and bits and for the repair of components.

# MECHANICAL DESIGN ENGINEERING

## ME 4182

PROJECT TITLE: Robotic Maintenance Module

LEADER: Mike Ayres

DATE: 18 October 1988

SUBJECT: Progress Report

The design of the robotic maintenance module has progressed into a mobile platform that can be towed behind a rover drilling rig as shown in the accompanying figure. The module will be light enough so that the rover will be capable of the towing procedure. Due to the time limits of this design course only the rover drilling rig will be considered in detail for the design of the module. However, the module will be easily adaptable to a skitter type drilling rig or for other tasks.

During the past week several robotic arms were looked at including the Puma robotic arm. This model was chosen on the basis that it has been used for numerous designs by the Jet Propulsion Laboratory for space telerobotics and was recommended to me by an engineer with many years experience in robotics. Information on the Puma robotic arm has been obtained along with studies for a generic arm attachment to pick up the various pieces required by the design.

Information on a 100 meter drilling system and its requirements has been located along with details of drilling bits and other essential information. The module is to be designed so that once the rover drilling rig is in place the module will detach itself from the rover and lower its three legs so that it may be free to walk completely around the rover for inspection, maintenance and operating assistance required for drilling.

PROJECT TITLE: Robotic Maintenance Module

LEADER: Mike Ayres

DATE: 25 October 1988

SUBJECT: Progress Report

The design of the robotic maintenance module has now evolved into a three legged walking platform that has motorized wheels on two of the legs as shown in the accompanying drawing. These wheels will be powered by DC motors to help the rover drilling rig from losing traction while towing the module. The wheels will be able to be lowered or raised on the tibia of the robotic leg thus allowing the weight of the module to be supported by the wheels.

The third robotic leg will have a hitch attached to enable hookup for towing to the drill site. A castor type wheel will also be mounted on the hitch leg so that the module may be driven and steered by the motorized wheels on the other two legs. This castor type wheel will be mounted so that it can be raised out of the way when the module is walking on its three legs.

# MECHANICAL DESIGN ENGINEERING

## ME 4182

PROJECT TITLE: Robotic Maintenance Module

LEADER: Michael L. Ayres

DATE: 1 November 1988

SUBJECT: Progress Report

Robot design in a vacuum environment was studied and left two basic ideas. The robot could be either totally exposed to the vacuum environment or it could be sealed in a type of suit which would allow the inside components to operate at atmospheric pressure. In order to expose the entire robot to the lunar atmosphere some major changes would have to be made including the lubrication systems, the surface finish and materials and the motors. It was decided that a type of seal for the robot would be a better choice than a component redesign.

The module has robotic legs and one robotic arm all of which will be rotary motion. A Thermionics differentially pumped rotatable platform is shown in the accompanying figure. The platform has three spring loaded seals which are 80% teflon and 20% graphite for low friction operation. Two chambers are formed which are pumped to different levels of vacuum.

The module is to have two video cameras one mounted on the robotic arm and the other mounted on the module base. These cameras primary task is to provide information about the position of the module relative to objects of interests. Subtasks include image segmentation, object recognition, and object location and orientation in some coordinate system. The cameras will provide the operators from earth the necessary visuals required for maintenance servicing and drill string loading and unloading.

# MECHANICAL DESIGN ENGINEERING

## ME 4182

PROJECT TITLE: Robotic Maintenance Module

LEADER: Michael L. Ayres

DATE: 8 November 1988

SUBJECT: Progress Report

In the past week the power and cooling requirements have been studied for the robotic maintenance module. The power for the module will come from a battery that will be capable of maintaining module operation for at least thirty hours. This battery will have to power numerous DC servo motors along with two computers and communication equipment as shown in the accompanying flowchart.

The cooling system for the module is to be a pressurized gas possibly hydrogen that will be pumped throughout the interior of the module for heating and cooling requirements. This fluid will be pumped to a heat exchanger mounted on the outside of the module so that it may be positioned toward or away from the sun depending on the heat transfer needed. Heat from another source will be needed when the module is operating on the dark side of the moon.

# MECHANICAL DESIGN ENGINEERING

## ME 4182

PROJECT TITLE: Robotic Maintenance Module

LEADER: Michael L. Ayres

DATE: 22 November 1988

SUBJECT: Progress Report

This week all the information collcted over the past eight weeks was collected and organized for the writing of the rough draft. The design of the cooling system was decided after the calculations for the heat produced by the electronics and drive motors was determined. The power supply was also chosen on the basis of average power required to operate the module. The drawings were labeled and dimensioned.