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Planetary Surface Exploration MESUR/Autonomous Lunar Rover

Capstone Senior Design Course Project Report

Department of Mechanical Engineering
University of Idaho
Moscow, Idaho 83843

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Associate Professor Larry Stauffer
Matt DiLorenzo, Teaching Assistant
Dave Austin, Raymond Ayers, David Burton, Joe Gaylord, Jim Kennedy, Dale
Lentz, Richard Laux, Preston Nance, Pete Peterson, Bob Picker, Sean Stack,
Kurt Vanausdell

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Abstract

Planetary surface exploration micro-rovers for collecting data about the Moon and Mars have been designed by the Department of Mechanical Engineering at the University of Idaho. The goal of both projects was to design a rover concept that best satisfied the project objectives for NASA-Ames. A second goal was to facilitate student learning about the process of design. The first micro-rover is a deployment mechanism for the Mars Environmental SURvey (MESUR) Alpha Particle/Proton/X-ray instrument (APX). The system is to be launched with the sixteen MESUR landers around the turn of the century. A Tubular Deployment System and a spiked-legged walker has been developed to deploy the APX from the lander to the Martian Surface. While on Mars the walker is designed to take the APX to rocks to obtain elemental composition data of the surface. The second micro-rover is an autonomous, roving vehicle to transport a sensor package over the surface of the moon. The vehicle must negotiate the lunar terrain for a minimum of one year by surviving impacts and withstanding the environmental extremes. The rover is a reliable track-driven unit that operates regardless of orientation which NASA can use for future lunar exploratory missions. This report includes a detailed description of the designs and the methods and procedures which the University of Idaho design teams followed to arrive at the final designs.

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Introduction

For the 1991-92 school year, the NASA groups in the University of Idaho (U of I) capstone senior design course were assigned to work on the development of micro-rovers for planetary surface exploration. The work for both semesters was done for the Universities Space Research Association (USRA) and the Intelligent Mechanisms group at Ames Research Center (ARC), Moffet Field, CA. Each semester had their own individual project with different customer requirements, which led to two different types of micro-rovers accomplishing their particular tasks. Students from the first semester worked on a rover for deployment of an instrument to collect data about the surface of Mars, while students from the second semester developed a rover for exploration of the Moons surface. This paper gives a complete description of both projects including the development of prototypes for each.

MESUR

Project Description / Background

The U of I mechanical engineering Fall senior design team was requested to design a deployment system for the instrumentation devices for the NASA's MESUR (Mars Environmental SURvey) project. The purpose of the MESUR mission is to emplace a globally distributed set of 16 landers on the Martian surface to make both short and long term observations of the atmosphere and surface. The MESUR concept was developed as a relatively low-cost, near-term approach to a Mars Network mission which would serve some of the objectives of the Mars science and Mission from Planet Earth. A mission of this sort will enable achievement of two general classes of scientific objectives that can not be met by any other means.¹ The first class is a group of objectives that require the

simultaneous operation of a number of globally-distributed surface stations. The primary examples are a global seismic network and a global network of meteorological stations. The second class is a group of objectives that require sampling of a large number of globally-distributed sites. Examples include geochemical sampling, high-resolution surface imaging and measurement of the atmospheric structure along entry profiles. Particular emphasis would be placed on hard-to-reach sites (polar deposits, rugged volcano flanks, etc.) that would be difficult or impossible to investigate by other means.

To meet these objectives AMES Research Center has developed a system of landers which will each contain the following instrumentation:¹

- **ATMOSPHERIC STRUCTURE EXPERIMENT**
 - Accelerometers + Pressure/Temperature Measurements
- **DESCENT and SURFACE IMAGERS (e.g. CCD Array)**
 - Descent: Black and White Imaging
 - Surface: Multiband Imaging
- **METEOROLOGY PACKAGE**
 - Atmospheric Pressure
 - Atmospheric Opacity
 - Temperature, Winds
 - Humidity (if possible)
- **ELEMENTAL COMPOSITION INSTRUMENT**
 - Alpha Particle/Proton/X-ray Spectrometer
- **3-AXIS SEISMOMETER**
- **THERMAL ANALYZER/EVOLVED GAS ANALYZER**

After discussing the MESUR project with Chris Leidic, the NASA representative, the design team decided to focus its efforts on the elemental composition instrument - the Alpha Particle/Proton/ X-ray Spectrometer (APX). Therefore, the design objective was to develop a system to deploy and transport the APX from the MESUR lander and obtain chemical analysis of rock samples on the Martian surface.

Customer Requirements

To develop this system, the U of I design team considered several different designs for accomplishing the required functions of the APX deployment system. The design parameters extracted from the MESUR documentation and NASA contacts for the APX deployment system are listed below.^{1,2}

- **Minimal Mass**
To make space travel economical, all payloads should be as light as possible. The MESUR project focusses on mass savings to justify its economical feasibility.
- **Minimal Size**
Each of the lander ports is the approximate size of a cylinder 0.25 M high and 0.20 M in diameter. The entire APX deployment system needs to be designed to accommodate this port size. In addition, by minimizing size, mass can also be kept to a minimum.
- **Simple Design**
The MESUR project is based on simplicity which results in low cost. A simple design would indeed be the most cost effective. The communication time delay from earth to Mars is 40 minutes. For this reason, the APX deployment system should be simple to operate. Movements should be easy to initiate and control.
- **Reliable design**
The MESUR project will be ongoing for 10 years, and it is essential all instrumentation is able to perform during this period. Failure to obtain the required data would be seriously detrimental to the success rating of the MESUR project.
- **Interior rock samples**
The rocks on the Martian surface are believed to have a thin outer crust. This crust is simply atmospheric dust that has accumulated over time. If the APX were to sample the rocks before the crust is removed, the data would reveal only the elements in the crust not those contained in the rock. Therefore, the outer crust needs to be removed before the APX can be placed on the surface. The data would then reveal the true elements contained in the surface rocks.

- **Multiple samples (if possible)**
The main purpose of the MESUR project is to gather as much data on Mars as cheaply as possible. Taking multiple samples of rock specimens in the immediate vicinity of each lander with the same APX deployment system would definitely enable a much larger spectrum of data to be obtained without the need for additional equipment and costs. Therefore, it would be ideal to design the APX deployment system with the versatility of taking multiple rock samples.
- **Low power requirements**
Each lander will be equipped with a Radioisotope Thermoelectric Generator (RTG) supplying 15 Watts (W) of power. The RTG supplies power to all equipment on the lander. The APX deployment system must operate on the least amount of power possible in order to ensure the power supplied by the RTG is adequate.
- **Compatible with the existing lander power source**
As describe previously, each lander is supplied with a 15 W RTG. In addition to operating on low power, the APX deployment system must have power requirements that are consistent with those supplied by the RTG.
- **Resistant to the Martian atmosphere and Space Travel**
The Martian atmosphere has temperature extremes from -160 C to 35 C. Many fine dust particles are also believed to be dispersed in the Martian atmosphere. The APX deployment system must withstand not only the temperature extremes, but also the wear and failure problems that result from the introduction of dust particles.
- **Impact resistance characteristics**
Upon landing on the Martian surface, the lander will hit with an impact that is equivalent to 40 times the static load. Impact stresses may also be introduced when the APX deployment system actually exits the lander and is placed (or possibly dropped) onto the Martian surface. Therefore, the APX deployment system must be designed to withstand the initial impact as well as exiting or on-surface impacts.
- **Orientation independent**
The landers do not experience a precise and controlled landing. Rather, the landers are expected to land in any position (horizontal, vertical, upside down, etc.). The APX deployment system must then be able to perform regardless of how the lander is oriented.

Concept Development

Functional Decomposition

The APX deployment system was designed using Quality Functional Deployment (QFD) methods of design. Appendix A goes through each step of the QFD method in detail. Using the above requirements from the customer, the functions that needed to be accomplished were developed. The three major functions of the design were as follows:

- Delivery of the system inside the lander from Earth to the Martian surface.
- Deployment of the system from the MESUR lander to the Martian surface
- Locate and obtain multiple rock samples on the Martian Surface

Each of these functions were broken down into smaller sub-functions which could be designed for individually. This resulted in the overall function structure outlined below

1.0 Delivery

1.1 Transport

1.1.1 Interface with existing MESUR lander

The APX Deployment System must fit inside the lander port and it must be able to survive transport.

1.2 Landing

1.2.1 Hold the APX Deployment System in place

The APX Deployment System must be kept in position during transport, entry and landing.

1.2.2 Protect the APX Deployment System

The APX Deployment System must be protected from damage during impact, and guarded against possible damage from foreign objects (sharp jagged rocks, etc.) while landing on the planet surface.

2.0 Deployment

2.1 Detach

2.1.1 Interpret Commands from NASA Control Center

All commands for control will be sent from earth so the NASA Control Center must initialize the operation.

2.1.2 Energize Deployment System

The APX Deployment System will only use power while in operation. This power needs to be provided by the lander's RTG when the system is operating.

2.1.3 Determine Exit Path from MESUR Lander

The landers will come to a rest in a variety of positions (upside down, angled, etc.). The best path out of the lander must be determined to ensure that the APX Deployment System will be deployed onto the surface.

2.1.4 Escape from MESUR Lander

After the best exit path is determined, the APX Deployment System must be able to escape from the lander. This should also be independent of lander position.

2.2 Orientation

2.2.1 Determine Orientation on Martian Surface

Once the APX Deployment System is out of the lander and on the Martian Surface, its orientation on the surface must be determined.

2.2.2 Correct Orientation

If the APX Deployment System is orientated such that it is unable to sample, the system will correct its orientation so that the sampling functions can be accomplished.

2.2.3 Check Orientation

To ensure that the system is in the proper position for sampling purposes, the orientation will need to be checked. If the orientation needs to be corrected, functions 2.2.1 and 2.2.2 will be performed again.

2.3 Initial Positioning

2.3.1 Locate Sample

A suitable sample on the Martian surface must be located.

2.3.2 Adjust Orientation to obtain Sample

The mechanism must be orientated so that the sample can be obtained in the simplest manner possible.

2.3.3 Move to Sample

Once orientation is adjusted, the APX Deployment System will move the APX instrument to the desired sample location.

3.0 Sample

3.1 Prepare Sample

3.1.1 Remove Outer Sample Layer

To obtain a satisfactory sample, the sample's outer crust must be removed. The outer crust is atmospheric dust deposits and brine, it is not representative of the elemental composition of the rock.

3.2 Make Contact

3.2.1 Remove Preparation Materials

Any equipment used to remove the outer crust must be removed before the APX can sample the specimen.

3.2.2 Orientate APX on Sample

The APX is orientated so that it can be placed onto the prepared sample surface.

3.2.3 Attach APX to Sample

The APX sensor head is pressed against the prepared sample surface.

3.3 Collect Data

3.3.1 Obtain Data

Using the APX functions, the elemental composition of the sample is determined.

3.3.2 Transmit Data back to Lander

This data is transmitted from the APX Deployment System back to the lander.

Morphology/Concepts/Evaluation

Using this function structure, a function morphology study was undergone to establish a means of performing these functions. See Appendix A for the morphology. In combining the components, four concepts were developed: a ribbon arm (remains attached to the lander and unrolls itself like a tape measurer), a folding arm, a spike-legged walker, and a tank-style rover. These were then compared using weighted characteristics and a plus, minus, and zero scale to determine the best concept, using the tank as an arbitrary datum. It can be seen in Figure 1 that the best overall design was the spiked-legged walker concept.

Customer Characteristics	Weight	ribbon arm	Concepts folding arm	legged walker	Datum tank
Light Weight	8	+	+	+	0
Small size	5	-	-	+	0
Minimum parts	7	+	-	+	0
Reliable	10	-	+	0	0
Impact resistant	10	-	-	0	0
Contact w/sample	10	0	0	0	0
Obtain sample	10	-	-	0	0
Low power	6	0	+	+	0
Temp. resistant	5	0	0	0	0
Weighted Results		-20	-8	26	0

Figure 1. MESUR design evaluation.

Detailed Design

From this analysis, the final design concept arrived at is the APX Deployment System which has two major components, the Tubular Deployment System (TDS) to hold the instrument in transportation and remove it from the lander, and the APX Walker to move the instrument to a sample. These two components will interface with the existing landers which are currently being designed at AMES research center.

Tubular Deployment System

This system is designed to secure the APX Walker inside the MESUR lander during transportation from earth to the Martian surface. The system interfaces directly with the existing lander design by fitting into one of the allocated instrumentation ports which are located around the lander's circumference. The major requirement of the design was that the system must be able to deploy the APX Walker from either side of the lander, since the lander is expected to tumble upon contact with the surface of Mars.

The final design solution is the Tubular Deployment System (TDS) which is shown with the APX Walker in Figure 2. The TDS consists of three concentric tubes that enclose the APX Walker and extends out to either side of the lander in a telescoping fashion. The innermost tube holds the APX Walker during travel to Mars and has 140 degrees of material cut out to allow the APX Walker to escape onto the surface. The middle tube is cut out 130 degrees for the same reason. The inner and middle tubes are guided by runners to allow them to move up and down in a straight path. The tubes and runners are constructed of rigid PVC, and are connected together with a solvent adhesive compatible with PVC. The inner tube is capped at both ends with thin (0.5 mm) aluminum disks. These disks are attached to the tube with rivets through tabs and epoxy on the mating surfaces. There is also a similar cap on the bottom of the middle tube, connected in the same manner as the inner tube caps.

The outer and middle tubes are connected together at the top (top being the end at which the APX Walker head is located) using a flange and pyrotechnic fastener system. The inner and middle tubes are connected together with a pyrotechnic fastener located in a hole drilled in the lower inner tube cap and the middle tube cap. In both cases, a spacer made of silicon rubber separates the connected components and provides vibration damping.

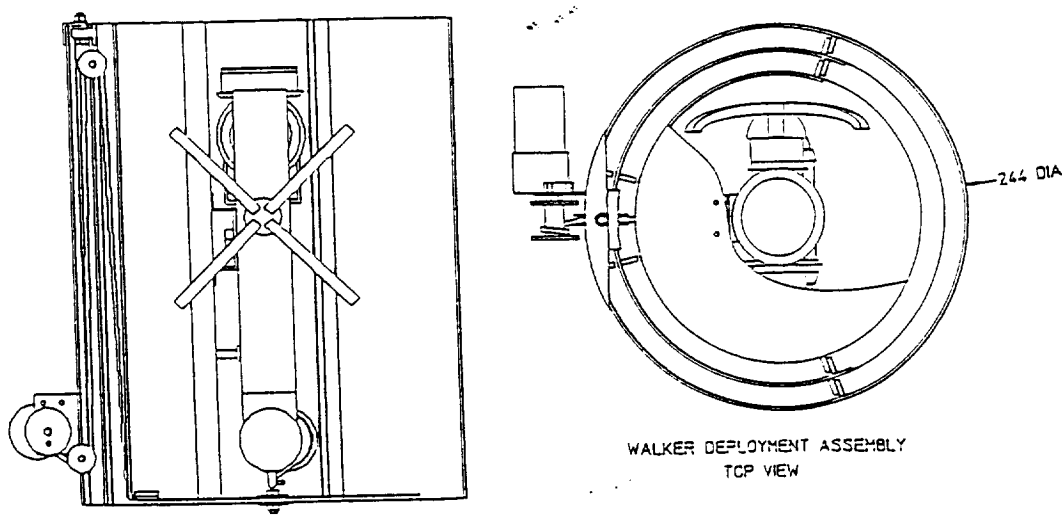


Figure 2. Tubular Deployment System with APX Walker; side and top view.

Vertical motion is provided through the use of an electric motor, nylon cable and pulley system. The cable is connected to the bottom cap of the inner tube using a compression clamp mounted to the inside surface. The cable is then threaded through the pulley located at the top of the middle tube, through the pulley on the outer tube, and finally through the hole on the take-up spool. The take-up spool is press-fit and then held by a set-screw on the shaft of a 1 R.P.M. reversible DC motor that supplies the motion. The advantage of using a motor, cable and pulley system is that once the APX Walker is on the surface, the motor can be reversed, lowering the TDS back into the port, therefore, eliminating the chance of blocking the surface imaging camera's view.

Once the lander reaches the Martian surface, the operators of the MESUR lander determines which side of the lander is not in contact with the surface. They will then put a current to the appropriate pyrotechnic fastener that, upon releasing, will allow either the inner tube or the inner and middle tubes to raise out of the lander, thus deploying the APX Walker to the correct side. The actual release of the APX Walker is accomplished through the use of another pyrotechnic fastener

connected to an internal support assembly. The internal support assembly consists of a section of rectangular aluminum tubing, locating pin and mounting flange connected between the caps of the inner tube.

The critical point in the TDS is the flange and pyrotechnic fastener system that connects the outer and middle tubes. These components are in a position critical to correct operation of the system. If a flange fails here, it means that the TDS will only work for the case of the walker being "upside down" in the inner tube upon landing. This upside down condition has a fifty percent chance of occurring. Therefore, this interface was designed with a factor of safety of 1.5, considering a 40g impact load (see Appendix B for Tubular Deployment System calculations).

The total mass of the Tubular Deployment System is approximately 2 kg (see Appendix C for mass calculations). With this mass, the motor must supply 25 oz.-in of torque to move the TDS, along with the APX Walker, up and out of the lander port (see Appendix B); however the TDS was designed with a 100 oz.-in electric motor to add a factor of safety.

APX Walker System

This system consist of three separate subassemblies: the Body Structure Assembly, APX/Grinder Assembly, and the Tether Assembly. These subassemblies together perform the following functions: adjust orientation, move to the sample, prepare the sample surface, position the APX onto the sample surface and transmit data collected to the lander. The APX Walker was designed symmetrically to allow the Walker to function right side up or upside down. The overall mass of the Walker is 1.01 kg and the center of gravity is located 86 mm from the rear of the Walker (see Appendix C). Shown in Figure 3 is the top view of the APX Walker (the side and front views of the APX Walker are shown with the TDS Assembly in Figure 2).

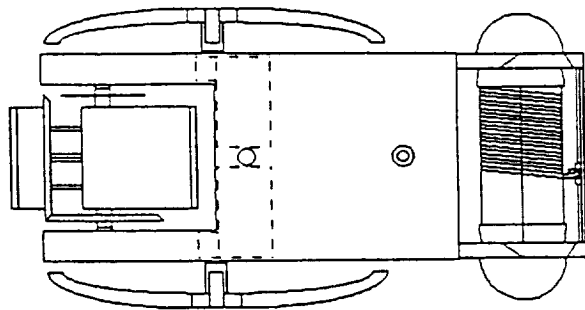


Figure 3. APX Walker Assembly; top view.

As shown in the figure, the APX/Grinder Assembly is positioned in the front of the Walker and the electric drive motors (phantom lines in Figure 3) are positioned behind the APX/Grinder Assembly and the Tether Assembly is located in the rear of the Walker.

Since the APX Walker System movement is provide by two electric drive motors, the characteristic of these motors needs to be addressed. Using the static mass of the APX Walker, it was calculated that each drive motor would need to produced a minimum of 26.9 oz-inches of torque . However, the design team recommends the drive motors produce 60 oz-inches of torque to give the Walker a factor of safety. The drive motors should be sealed to ensure dust and particles do not enter the electric motors. Two 15 volt, 1 R.P.M., DC electric motors, one for each set of legs, would be required for controlling the movements of the Walker on Mars. The motors drive the two sets of legs on the APX Walker and would have a power requirement of approximately 1.0 Watt (depending on motor selection). However, the University of Idaho team was unable to find an electric motor which produced this amount of torque and is compatible with the body assembly. Therefore, further research into electric motors would be required to finalize the drive motor selection.

The walking motion of the APX Walker is provided by two rotating spindles. Each spindle has four elliptical legs which are press fit into the spindle. The spindles are connected to the electric motor's drive shafts using a small set screw. The legs are produced from 7 mm square rod which is bend into a elliptical shape as shown in Figure 2. An elliptical shape was chosen to allow the Walker to flip over easier if it topples onto its side. Square rod was chosen to gain additional traction while the Walker is moving and since the elliptical shape of the legs could be readily produced.

The overall physical characteristics of the APX Walker are listed in the table below.

APX WALKER PHYSICAL CHARACTERISTICS	
HEIGHT (with Legs)	160 mm
(without Legs)	60 mm
LENGTH	255 mm
WIDTH (with Legs)	144 mm
(without Legs)	100 mm
APPROXIMATE MASS	1.01 kg
CENTER OF GRAVITY (Measured from the Rear)	86 mm
VOLUME DISPLACEMENT (with Legs)	5875 cm ³
(without Legs)	1530 cm ³

The APX Walker has the following operational characteristics:

APX OPERATIONAL CHARACTERISTICS	
POWER REQUIREMENTS (Including grinder and drive motors)	2.5 Watts
MAXIMUM SPEED	0.3 meters/min
TURNING RADIUS	80 mm
OPERATING RANGE	approximately 2 m radius
VERTICAL CLEARANCE	58 mm

The values listed above are obtained from combining the three subassemblies of the APX Walker. A physical and operational description of each subassembly is provided in the following sections.

Body Structure Assembly

The backbone of the APX Walker is the Body Structure Assembly which is shown in Figure 4. This assembly consists of eight separate parts which are joined together with aluminum braze.

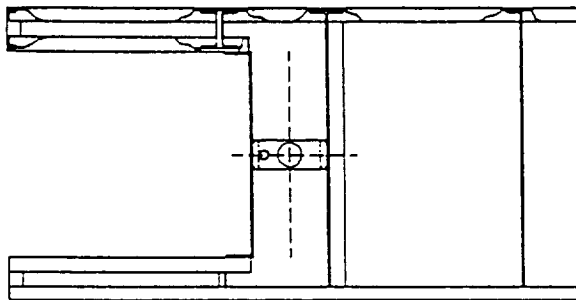


Figure 4. Body Assembly.

The function of the Body Assembly is to provide interfaces for the three APX components: the APX/Grinder Assembly, the Tether Assembly, and the electric drive motors for the Walker. Besides providing the interfaces to each of these components, the Body Assembly has the function of interfacing with the Tubular Deployment System (TDS).

The Body Assembly is simple in construction with all the parts made from 2024 T4 Aluminum alloy. This light-weight alloy gives the APX Walker the strength required to hold the three components in the Walker and absorb the impacts which will be experienced by the Walker. This material also has reasonable machining characteristics which are needed in forming these parts.

The physical characteristics of the Body Assembly are as follows:

- The Body Assembly weights 0.1223 kg (this figure does not include the Aluminum braze which holds the parts together).
- The center of gravity of the Body Assembly is located 120 mm from the back of the assembly.
- The constructed body is 35 mm in height and 195 mm in length
- The APX/Grinder Assembly fits inside the 82.5 X 70 mm opening in the front of the Body Assembly. The APX/Grinder Assembly is secured to the body by 7 mm Aluminum tubing press fitted into bearings.
- The Tether Assembly is positioned inside the 10 X 98 mm opening in the rear of the Body Assembly. The Tether Assembly is connected to the body using eight 3 mm bolts and Aluminum brazing around the interface of the two assemblies.

The following table lists the eight separate parts which are used in the body assembly and a brief description of their function.

BODY ASSEMBLY COMPONENTS		
Part Name	Qty.	Description of Function
Outside C-Channel	2	Provides overall support to the Walker and mounting areas for the electric drive motors
APX C-Channel	2	Provides an interface for the APX/Grinder Assembly
Front I-Beam	2	Provides rigidity to the APX C-channel and Outside C-channels
APX Cross Rib	1	Provides support for the APX C-Channel and sealing surface for the electric motor compartment.
Middle I-Beam	1	Provides support and sealing surface for the electric motor compartment
Rear I-Beam	1	Provides the support and interfacing surface for the Tether Assembly
Front Covers	2	Joins the Outside C-channel and APX C-channel at the front of the assembly.
Mounting Block	1	Provides an interface which holds the APX Walker into the TDS

The physical dimensions of the Body Assembly parts are given below. All channels are constructed of 1 mm thick aluminum sheets and I-Beams are milled to required dimensions.

- The outside C-channel is 35 mm high X 195 mm long with a 5 mm flange. Drilled into the flange are twelve holes which are used to secure the covers of the Body Assembly. The mounting holes for the electric motors are also drilled (as required) into the channel.
- The APX C-channel is 35 mm high X 82.5 mm long with a 5 mm flange. Drilled into the flange are 6 holes which are used to secure the cover of the Body Assembly. The 7 mm interfacing hole for the APX/Grinder Assembly is drilled into the middle of this channel.
- The Front I-Beam is 33 mm high X 13 mm long with a web thickness of 2 mm. The web thickness provides additional support required to hold the APX/Grinder Assembly.
- The APX Cross Rib is 35 mm high X 70 mm long with a 9 mm flange which connects the Cross Rib to the APX C-channel.
- The Middle I-Beam is placed behind the motor mounting section of the Walker to provide structural support for the motors. The Middle I-Beam is 35 mm high X 98 mm long with a web thickness of 1 mm. On the rear side of the I-Beam are two flanges with six holes which secure the covers of the Body Assembly. In the middle of the I-Beam is an 8 mm hole which allows the control wires for the solenoids and electric motors to pass.
- The Rear C-Channel is 33 mm high X 98 mm long. This channel has a hole in the middle of the channel which passes the control wires for the APX/Grinder, solenoids, and electric motors. The channel also functions as an interface for the Tether Assembly.
- Connecting the Outside C-channel to the APX C-channel is accomplished by the Front Covers. The covers are 35 mm high X 35 mm X 13 mm wide. The covers have 5 mm flanges around the perimeter which mesh with the Outside and APX C-channel flanges to produce an uniform connection.
- As mentioned above, the Mounting Block is used to secure the APX Walker into the TDS. The block is 35 mm high X 25 mm long and 10 mm high and is milled out to reduce the weight of the part. The Mounting Block has a M8 X 1 threaded hole drilled into the top and two 8 mm holes in sides of the block. The 8 mm bolt in the TDS is threaded into the top hole to connect the APX Walker to the TDS. The other two holes provide passages for the control wires of the Walker.

Besides the eight parts mentioned above, the Body Assembly includes the two cover plates which are held onto the Body Assembly using 3 mm sheet metal screws. The cover plates provide two functions: additional structural support, and a sealing surface for the electric motors and mechanical parts inside the body assembly. When the covers of the body are placed on the Walker a thin film of silicon gel is placed on the interface so that a seal is produced. This seal protects the internal moving parts of the Walker from the harsh Martian dust and atmosphere.

APX/Grinder Assembly

Before developing design concepts for the APX/Grinder Assembly, the functions that the assembly must perform were detailed. These functions are listed below.

- **Prepare surface**
The brine/crust on the outer surface of the samples needed to be removed so accurate sampling can be achieved.
- **Position APX**
After the surface is prepared, the APX must be positioned onto the prepared surface. This must be performed accurately to ensure precise sampling.
- **Hold APX Against Surface During Sampling**
The APX must be held securely against the surface of the sample until the sampling is completed.

The design concepts of the APX/Grinder Assembly began developing during the Function Morphology portion of the QFD design method. First a method of preparing the surface was selected. A disk grinder was chosen for this task for several reasons. First, a grinder seemed to be the simplest tool for removing the brine (as compared to a belt-driven sander, pneumatic chisel, drill and catch tray, circular saw). Secondly, the base of the APX is circular, and a disk grinder would remove the brine in a circular area, thus the APX could rest firmly on the surface of

the prepared sample. Lastly, the power requirements could be kept low if grinding pressure were kept to a minimum. Therefore, a high R.P.M., low torque electric motor would be used to power the grinder.

After the method of removing the brine was established, the design team then had to develop a simple way of positioning the APX onto the prepared surface. The design team decided that positioning could be done most feasibly by positioning the APX and grinder faces 180 degrees apart and rotating the whole subassembly to switch the positions of them. The rotation method would keep the width to minimum and could be readily accommodated in the APX Walker design.

The design team then developed the following requirements that the APX/Grinder Assembly concept was required to fulfill:

- To keep simple and minimize power requirements and mass, the APX/Grinder Assembly should be able to rotate without requiring an additional electric motor other than the grinder motor.
- The rotation should be controlled so when the grinder is being used the assembly will not be continually rotating the APX and the Grinder.
- Grinding and sampling needs to be accomplished in a variety of positions. The grinder and the APX need to be positioned at angles other than simply horizontal with the APX Walker body.
- Slight, but constant grinder pressure should be kept while grinding the sample surface.
- The rotation mechanism should be bi-directional because the wire would eventually twist after taking multiple samples.
- The controls for the APX/Grinder Assembly should be integrated with the Walker control panel and the lander's imaging system.

The APX/Grinder design is shown below in Figure 5 (the top view is in the APX Walker Assembly, Figure 4).

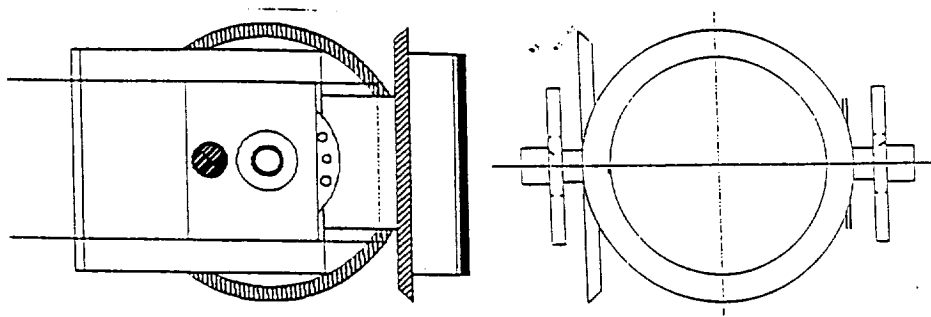


Figure 5. APX/Grinder Assembly; side and front view.

The APX/Grinder Assembly contains the following components: one grinder disk, two beveled gears, two solenoids, one APX/Motor cage, and one indexed positioning disk. The grinder disk is made of Synthetic Sapphire to ensure it is long lasting and capable of grinding to a very smooth surface. One beveled gear is coupled to the backside of the grinder, while the other is located on the axle (on which the entire assembly rotates around). One solenoid engages the side beveled gear when flipping the grinder and APX, and the other solenoid holds the entire assembly at the desired angle from horizontal. To hold and protect the APX and motor, a cage or container is used. The APX and grinder motor are simply mounted inside the cage. The positioning disk is located on the axle opposite the beveled gear and has indexed holes so the positioning solenoid can be used to hold the assembly at the desired angle from horizontal.

All of the components listed above combine to make up the APX/Grinder Assembly. The operation sequence below describes how this assembly operates. It is assumed that the sample has been located and the APX Walker is already at the sample location.

- 1) The side beveled gear is engaged by one of the push-pull solenoids. It is now held stationary with respect to the APX Walker frame.
- 2) The positioning solenoid is now released.

- 3) The grinder motor is turned on and the assembly rotated up or down (depending on the direction of the grinder motor). This is achieved by the coupling of the front beveled gear to the grinder motor.
- 4) When the desired grinder position is achieved, the positioning solenoid is engaged.
- 5) The side beveled gear is disengaged and grinding begins.
- 6) Grinding pressure is kept by very slight movements of the APX Walker legs as needed.
- 7) After grinding is completed and the sample surface is prepared, the APX must be positioned. The grinder motor is turned off and the side beveled gear is again engaged.
- 8) The positioning solenoid is released and the grinder motor is turned on to rotate the assembly.
- 9) The assembly rotates 180 degrees, the grinder motor is turned off and the position solenoid then engages to hold the position.
- 10) Any slight positioning of the APX is done by moving the APX Walker slightly forward or backward.
- 11) Data is then transmitted back to the lander.

Tether Assembly

When the Walker was being designed, several methods of supplying power and control to the Walker were investigated. The end result was the Tether Assembly. To make the tether idea feasible for the Walker, it had to perform the five following functions: supply power for the APX Walker drive motors, grinder motor, and solenoids, enable the tether to be unrolled or rolled from the spool without being wrapped up in the APX Walker's legs, allow the tether to operate when the Walker is upside down or right side up while moving either forward or reverse, assist the Walker in sliding side-to-side on the Martian surface during turns, and enable the APX Walker to have an operating range of 2 meters from the lander.

Figure 6 shows the top and front view of the Tether Assembly. As the figure shows, the tether assembly has four major parts which include the spool, wheels,

worm gear mechanism, and the gears which connect the other three parts. In using only four major parts, the tether is simple and reliable. The assembly's mass is 0.34 kg (see Appendix C), which ensures the wheels and spool remain in contact with the surface while the walker is moving.

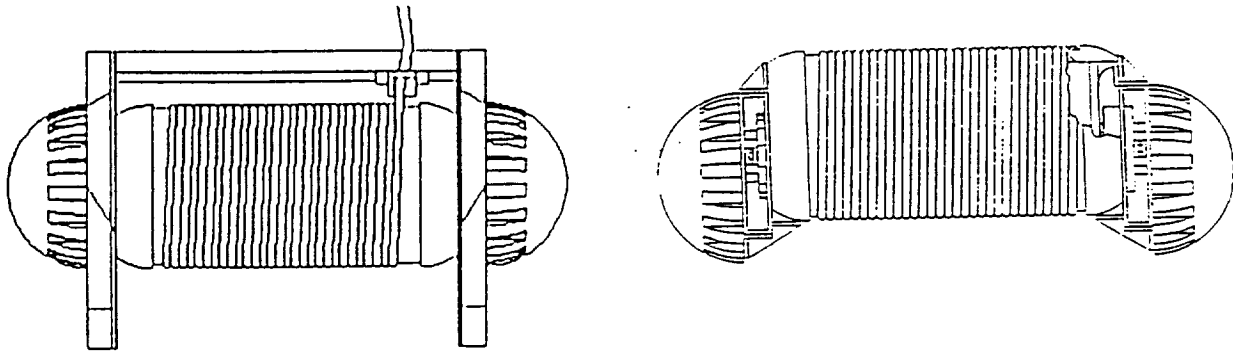


Figure 6. Tether Assembly; top and front view.

Since the MESUR project encompasses seven to nine years, the Tether Assembly was chosen to supply the power to the electrical motors, because batteries aren't possible and a separate RTG would be too massive to place inside the Walker. The power for the drive motors, grinder motor and solenoids is supplied to the Walker by a four meter tether connected to the lander's RTG. Inside the tether spool are the electrical brushes which distribute the power supply to the electrical components. Since the tether is only used to supply power to the Walker, the data from the APX is transmitted back to the lander using radio waves.

Since the tether has few parts, the assembly process is simple. The tether body is constructed of two pieces of 1 mm aluminum sheet which are stamped to the required dimensions and brazed together. The electrical brushes and gears for the spool and the worm gear are placed into the tether body. The brushes, gears, the worm gear and its follower, are produced commercially. Lexan (high impact

plastic) wheels and the spool are added to the tether body. After the Tether Assembly is constructed, it slides into the end of the APX Walker and is secured with 3 mm screws and aluminum braze.

When the Tether Assembly is connected to the APX Walker, it functions in the following manner:

- The spool is used as a wheel when the Walker is right side up. In this configuration, the tether simply rolls out as the APX Walker moves forward, and rolls up while it moves backwards.
- The wheels are used when the APX Walker is inverted. These wheels, directly coupled to the spool, cause the tether to be rolled in and out. Only two gears are necessary to facilitate this action, one connected to the spool, and the other connected to the wheels.
- As the spool or wheels rotate, a worm gear mechanism (like those found on fishing reels) guides the tether so that it will not bind up and get tangled on the spool or in the Walker legs.
- The spool ends, wheels, and the back end of the APX Walker are rounded so the Walker could turn around on the Martian surface.

Overview of the APX Deployment System Operation

The following theoretical operational sequence describes the deployment and operation of the overall APX Deployment System (the TDS and APX Walker System):

- 1) The TDS system secures the APX Walker into the MESUR lander port during transport through space and onto the Martian surface.
- 2) After landing on the Martian surface, the imaging system on the lander is used to determine the appropriate escape path for the TDS and APX Walker.
- 3) The TDS lifts the APX Walker out of the lander port via the predetermined escape path.
- 4) A pyrotechnic fastener which holds the APX Walker into place is activated causing the APX Walker to fall onto the lander or the Martian surface (depending on lander orientation).

- 5) Once the Walker is disconnected from the TDS, the Walker's orientation will be determined using the Imaging System on the lander. Correcting the orientation will be initiated by control signals sent from earth.
- 6) The lander's imaging system will locate a suitable sample for the APX.
- 7) Commands sent from earth will guide the APX Walker to the desired sample site. The amount of power supplied to each drive motor will control the movements of the Walker. As the walker moves to the sample, the tether connected to the lander will unroll using the Tether Assembly.
- 8) Commands sent from earth will position the grinder on the desired sample. The grinder will remove the outer crust on the sample and the APX will then be placed onto the prepared surface.
- 9) The APX will then collect elemental data from the sample and the data will be transmitted back to the lander via radio transmissions.
- 10) Additional samples can be located using the Imaging System on the lander and the sampling procedure can be repeated until all desired sample data is obtained.

Discussion

While developing the APX Deployment System, the University of Idaho Design Team built and tested a Walker prototype. This prototype was very similar in overall dimensions, mass, and operation to the final APX Walker design. Constructing and testing this prototype allowed the design group to make some observations concerning the operation and manufacturing of the APX Walker.

If the desired range of the APX Walker is increased greatly, changes will need to be made in the imaging system which locates samples. Currently, the camera positioned on the lander is expected to perform all required imaging functions. By increasing the range, the Walker might be obstructed from the on-lander imaging system. Therefore, the APX Walker may require its own imaging system that is located on the Walker.

Since the parameters of the lander are not set, the APX Walker and TDS can be readily scaled if modifications to the lander or port sizes deem it necessary. The dimensions of the APX/Grinder can also be scaled to account for any changes in the dimensions of the APX.

If the lander were to experience an impact of considerably less than 40g's, the strength of the APX Walker and TDS could be decreased. This would result in a mass and cost savings.

Due to the simplicity and precision of control, the controls system can be readily integrated with a computer control center. This system could incorporate software that would enable the user to input a vector pattern thereby automating the APX Walker movements. This would save operating time because the operator would no longer have to wait for the time delay between each input.

Conclusions

The systems designed by the University of Idaho Design Team will satisfy the required functions and parameters which were essential to the MESUR project. The design team has made the following conclusions based on calculations concerning the final design, and by building and testing the prototype Walker.

- The APX Walker mass is within the limits of the design criteria (1.01 kg). The Aluminum construction of the Walker provided sufficient rigidity and support for internal components; however further reduction in the Walker mass could be accomplished by using less dense materials and alloys.
- The prototype was easily controlled using simple 12 V power sources. Upgrading the electrical components of the Walker for use with the lander's RTG power source (15 V) would require little effort and provide the same simple operating characteristics.
- Costing approximately \$900, the APX Deployment System is an economically feasible alternative for the MESUR project.

- The prototype's maneuverability was impressive. Having a small turning radius and slow speed, the Walker prototype maneuvered easily around and over obstacles.
- The prototype's APX/Grinder Assembly also displayed the ability to sample at various locations, heights, and sample surface angles.
- The Tether Assembly on the prototype performed well and the tether did not tangle with the walker legs; however power was not supplied to the prototype using the brushes inside the spool.
- The Walker legs on the prototype were 7 mm circular rod and the walker experienced slipping during operation. Therefore, in the final design the legs are constructed of 7 mm square rod. This will help alleviate the traction problem by increasing the surface area in contact with the surface.
- Several samples can be obtained at each landing site increasing the value of the MESUR mission.

Autonomous Lunar Rover

Planet Surface Exploration

The National Aeronautics and Space Administration is developing an automated planetary exploration system to search for minerals on distant planets. The system involves deploying many autonomous vehicles to randomly search the surface of a planet for extended periods of time. The small, simple vehicles will wander around transporting a sensor package, searching for specific substances such as water or minerals. Once the sensor package detects the substance, it marks the location and reports it back to the command base.

For this project, these autonomous roving vehicles will move about the surface of the moon for over a year. During this time, many of the vehicles may become stranded, stuck, disabled, etc. But the idea is that, if the substance exists, there is a factor of safety built into having several rovers so that at least one vehicle should encounter the substance during its period of operation.

This lunar exploration project will provide NASA two major benefits. The first benefit is the collection of data about the lunar surface. Each rover's sensor package can be programmed to search for a specific element or compound, allowing for a wide-range search. These data will help broaden our understanding of the formation of the planets and moons of our solar system. The second benefit is an operational test of the exploratory technology which, if successful, will be applied on future planetary exploration missions.

Project Description / Background

The Universities Space Research Association (USRA), in conjunction with NASA, assigned the Spring senior design class NASA group, the task of designing an autonomous roving sensor platform capable of transporting a payload across the lunar surface, and constructing a working prototype. The payload, consisting of

the sensor package and the power system, will be provided by another contractor. Since the payload has yet to be defined, its specifications will be assumed for design purposes.

The rover will require a rechargeable or regenerative power supply in order to cover as much terrain as possible during its one year life. The communications requirements will be limited due to mass and power constraints, but the vehicle should relay its position to other vehicles and/or a base station to be relayed back to earth. The vehicles should be capable of limited cooperative behavior, so that they do not duplicate effort.

Project Objectives

The project objectives include creating a vehicle that is autonomous in the sense that it does not require any contact with humans; it does not require remote directional or intelligent control; it can avoid obstacles; and it can negotiate the lunar terrain for approximately one year. The vehicle must be durable enough to withstand a tumble down a crater and mobile enough to traverse rugged terrain. The navigation and obstacle avoidance mechanisms should be reliable and compact. It is understood that a certain percentage of the rovers may not find what they are searching for, may malfunction, or may be disabled before the mission is complete. In order to increase the chances of a successful mission, several of the units must be deployed at one time. The vehicles must be lightweight and inexpensive so that a large number of rovers can be transported and deployed in a single trip to the moon.

Problem Statement

The customers for this project are Terry Fong, Assistant Professor Larry Stauffer, and graduate assistant Matt DiLorenzo of the University of Idaho who represent the USRA and the Intelligent Mechanisms Group at Ames Research

Center (ARC). Also, as part of a nation-wide program, Dr. Stauffer and Mr. DiLorenzo will be presenting the autonomous roving sensor platform at the USRA summer conference in Washington, D.C. in June 1992.

Customer Requirements

Below is a list of the customer requirements used in the development of the problem statement.

1. Functional Capabilities:

The device must be capable of the following tasks:

- Transporting the sensor package and power supply.
- Continuously operating for one year.
- Operating independent of human intervention.
- Successfully negotiating the lunar terrain.

2. Physical Characteristics:

The device must feature the following physical characteristics:

- Small and lightweight to minimize the cost of deployment.
- Resistant to the effects of the lunar environment.
- Strong and durable, allowing it to withstand physical shocks.

3. Assumptions:

The following features are assumed to be provided by the customer:

- Reliable, regenerative, on-board power supply.
- Sensor package and controlling software.
- Deployment of the device onto the moon's surface.

Problem Statement

The customers need a reliable, autonomous vehicle to transport a sensor package across the lunar surface for a minimum of one year as part of their space exploration program. The vehicle should be as small and lightweight as possible while still possessing the ability to transport its cargo and negotiate the lunar

terrain. The vehicle must be capable of continuous operation in the lunar environment. After being placed on the surface of the moon, the vehicle must operate independent from human intervention. This type of vehicle is also needed to test the reliability of the design for possible application on other planets.

Background Research

Lunar Environment

A primary concern during the early stages of the design process was overcoming the obstacles of the lunar terrain, atmospheric conditions, and extreme temperatures. These characteristics of the moon restricted the use of certain materials and components which would normally be used in the design of a roving vehicle for use in the earth's environment.

The lunar terrain is made up of numerous valleys and highlands, as well as several million craters. As Cooper states, "The white areas you see on the moon represent craggy highlands and the black areas of the moon represent Maria (Latin term for tranquil seas) which are the smooth and level lowlands."³

Large meteorites have crashed into the moon's surface because there isn't any atmosphere to disintegrate them. The various craters found on the moon are formed from these falling meteorites. The debris from impact with the moon created several million boulders ranging in size from a few inches in diameter to large, immovable boulders several thousand feet in diameter.

According to Cooper, "Lunar craters range in diameter from a few inches to 160 miles, possibly much, much more. Regardless of their size, they are shallow depressions." Many of the larger craters have a surrounding ring around the

circumference of the crater which range in height from a few hundred feet to 4920 feet. The maximum slope of crater walls is approximately 50°.

The dust on the surface of the moon poses several problems as well as the rugged terrain, boulders, and craters. The dust layer is composed of very fine particles (15 μ m), one to two centimeters in depth. Below this layer of fine dust is a hard, thick lunar crust.

The atmospheric pressure on the moon is 10^{-13} times that on the earth. Because there is essentially no atmosphere on the moon, the lunar environment can be considered a vacuum. This fact creates problems in component selection because the components requiring lubrication cannot use typical lubricants, such as oil and grease, as they tend to "gas out" in a vacuum.

With no atmosphere to block most of the sun's radiation, there is an extremely wide range of temperatures on the moon. At the poles of the moon, the temperature never rises above -253°F. During a lunar day (approximately fourteen earth days) the equatorial surface temperature rises to about +250°F. Then after sunset, the temperature quickly drops to -250°F or lower.⁴ The moon's gravity is approximately one-sixth that of earth's ($g_{\text{moon}} = 5.32 \text{ ft/s}^2$).

Previous Rover Projects

In recent years, several lunar vehicles have been designed. These designs, although very different from our scope, gave us a basis from which we could begin our lunar rover conceptual design. The most recognizable rover design is that of the Apollo program which was used on the moon in the late 60's and early 70's. The Apollo vehicle was used for lunar exploration and astronaut transportation. The rover is a manned four-wheel vehicle with a unique tire design made of woven steel wire and girded with titanium chevrons.³

Battelle Columbus Laboratories in Columbus, Ohio designed a second vehicle. This rover is an unmanned, six-wheeled vehicle that operates autonomously and is self-deployable. It would be used to map certain areas and construct antenna sites on the lunar surface.

A third design, encountered in our research, is a rover designed by NASA. This design was intended for Mars, rather than the moon. The vehicle is an unmanned, six-wheeled unit that would collect surface samples while exploring the Martian surface. The Mars rover has a mass of approximately 700 kg and is transported to the surface in its own lander. Though this design greatly exceeds our project's scale, it was accompanied by the design process used by NASA. This example of a detailed design process was a major benefit to our group.

Research on Tracks vs. Wheels

For the first half of the semester, two groups worked separately on the project. The groups then combined at midterm with two similar but different concepts. At this point, our customer suggested that the newly formed group re-evaluate both concepts with set criteria to determine the better design. This re-evaluation of the designs centered around the fundamental difference between the two concepts, to have a wheeled rover or one with tracks.

The re-evaluation of the concept started with a literary search. This search revealed Dr. M.G. Bekker and some of his works. Dr. Bekker's research was an intricate part of the lunar roving vehicle design team for the Apollo program and is considered an expert in his field. In his book Introduction To Terrain Vehicle Systems, Dr. Bekker states:

"A few years ago, I was engrossed with proving that in lunar surface locomotion, the wheel cannot be challenged by exotic solutions. It soon became clear, however, that conventional forms - particularly of small vehicles - may be unacceptable and this led me to a methodical search for new vehicular forms and elements."⁵

Though this statement does not include a proof of any sort, Bekker may have answered the entire re-evaluation process with it.

In his first Book, Dr. Bekker demonstrates a method to calculate the tractive force for both a wheeled and track vehicle. The tractive force is the force the track or wheel exerts on the ground and is dependent on soil conditions, c and ϕ , soil cohesion factor and shearing angle, respectively. This tractive force results in thrust for the vehicle; therefore, the larger the tractive force is the larger the vehicle thrust will be. The equations to calculate the tractive force are as follows:⁵

$$T_n = 4A_w c + W \tan(\phi) \quad (\text{for the wheeled vehicle})$$

$$H_n = 2A_t c + W \tan(\phi) \quad (\text{for the track vehicle})$$

Where T_n is the tractive force for the wheeled unit and H_n is the tractive force for the track unit. For both equations W is the weight of the vehicle, c is the soil cohesion factor and ϕ is the shearing angle of the soil. A_w is the contact area for a rigid wheel and A_t is the contact area for the track.

Figure 7 shows a comparison between two vehicles of equal weight (approximately equal to the engineering requirement for this project) on the same soil, one with rigid wheels and the other with tracks. It shows that a track system will create a larger tractive force in all soils except when the cohesion is zero ($c = 0$). This larger tractive force is due to the greater contact area the track has over the wheel. When the cohesion is zero ($c = 0$), the tractive effort for both systems is equal to $(W \tan(\phi))$. Note, both equations are soil dependent and exact soil cohesion factor for the moon is not on record, so parametric studies for a range of cohesion factors and shearing angles were conducted to verify the conclusion that the track will create a larger tractive force; consequently, a larger vehicle thrust. The track concept results in larger tractive force and vehicle thrust than the wheel concept. The re-evaluation of the design concept and the results of these calculations resulted in the selection of the track over the wheel.

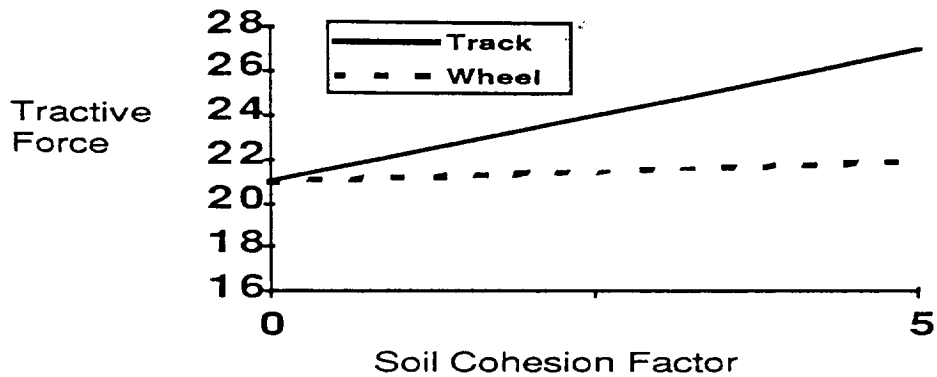


Figure 7: Tractive force vs. soil cohesion factor.⁵

Design Specifications

Customer Wants and Their Order of Importance:

- | | |
|-------------------------------|------------------------|
| 1. Transport sensor package | 6. Small size |
| 2. Durable | 7. No maintenance |
| 3. One year life span | 8. Easily manufactured |
| 4. Light-weight | 9. Inexpensive |
| 5. Withstand lunar conditions | 10. Few moving parts |

Engineering Requirements

- Mass less than 20 lb_m
- Volume less than 1.0 ft³
- Withstand the temperature range -157°C To +121°C
- Operate at gravity equal to 5.32 ft/s²
- Operate at pressure is 10⁻¹³ times that of Earth
- Withstand a 30 ft freefall on to an unyielding surface on the moon.

Specifications

This list contains the "musts" and "wants" for the rover design project.

MUST:

- transport sensor package/power supply
- mechanical lifetime of one year (minimum)
- survive a 30 ft fall onto a non-yielding surface on the moon
- negotiate terrain (avoid obstacles, climb, descend, etc.)
- successfully operate in the lunar environment
- require no maintenance, human interaction
- single person deployable

WANT:

- smaller than 1.0 ft³, 20 lb_m (w/o sensor package/power supply)
- minimum number of moving parts
- solar energy collection capability
- low cost

NOT RESPONSIBLE FOR:

- the black box/sensor package (electronics with power supply)
- signal transmission (assumed to be part of the black box)
- packaging for transport
- deployment

Concept Development

Functional Decomposition

An important step in the lunar roving vehicle design process was the functional decomposition. The functions of the rover can be broken into seven parts, which are as follows: locomotion, traction, sensor support and protection, self-righting, obstacle sensing, and obstacle negotiation.

Locomotion, the method of translating rotational motion into linear motion, and traction, the method of gripping the traveling surface, are related functions that deal with methods of moving the unit across the lunar surface. Locomotion and traction are the primary functions performed by the rover since the rover's mission is to transport the sensor package over the lunar surface.

Another set of functions are related as were locomotion and traction; they are obstacle sensing, determining an obstacle that prevents forward travel of the unit, and obstacle negotiation, how the rover avoids an obstacle. The lunar surface consists of many large rocks which will impede the forward progress of the rover. The rover must be able to identify these obstacles and maneuver around them or the rover will be destined to be pushing against immovable objects.

Maneuverability, steering the unit, is required to perform the previous function obstacle negotiation. If the rover's forward progress is impeded and it does not possess steering capabilities, it will travel the same path from which it

came until another obstacle presents itself. Basically, the rover will continue to travel back and forth between the two obstacles. Steering enables the rover to avoid obstacles and to travel a new path if the original path is obstructed. Steering may also be necessary if the sensor has to direct the rover to a particular position from which it has received a signal.

Another function that is very important to the survival of the unit is self-righting, the method of righting an overturned vehicle. The lunar surface is not flat; it possesses many craters and rocks. Some craters have inclines as great as 50°, and the rover may tumble into one of these craters at any given time. The unit must be able to deal with being upset or be destined to sit on its back like an overturned turtle as no one will be present to perform the task.

The final function is to support and protect NASA's sensor package. The whole purpose of this unit is to transport the sensor over the lunar surface. The rover must be able to transport the sensor to complete the mission. Quite often the travel will include a tumble or fall. This can damage the sensor, and the unit is a loss. Preservation of the sensor will increase the odds for a successful mission.

Morphology

Once the functions of the rover had been decomposed, the next step was to determine methods for performing each individual function. For this step, the group did not limit itself to the rover's functions, though, as it included the mechanical actuator, protection from the environment and alternate power supply. This step, commonly referred to as the morphological study, involved some minor research and brainstorming for possible methods.

The morphology for the lunar rover project is included in Appendix A. Note that the protection from the environment and alternate power supply were not included. Protection from the environment and alternate power supply are detail

design characteristics not conceptual design characteristics. The small numbers in each major subject box indicates the position where that subject was addressed for concept building.

Concepts

In determining design concepts, the characteristics of significance in selecting options from the morphology to perform functions determined in the functional decomposition were determined and weighted . These characteristics fell into four basic groups: physical characteristics, design simplicity, survivability, and mechanical reliability.

The physical characteristics of concern were the rovers size, single person deployment ability, and the vehicle's weight. Each of these characteristics is interdependent to a degree. Due to the cost of lifting objects to the moon, about \$5000 per pound, minimizing the weight and size is very important. Single person deployment was not a high priority since generally more than one astronaut is involved in space missions.

Design simplicity included such characteristics as few parts total, few moving parts, ease of manufacture and autonomy. Since NASA specified a limit as to the cost of producing each rover, minimizing the total number of parts and number of moving parts as well as decreasing manufacture time would reduce unit cost. A simpler design would also ensure the autonomy of the vehicle as stated in the problem statement.

The third group, survivability, included wide temperature range operation, impact resistance, environmental resistance and terrain and obstacle negotiation. Each of these characteristics is important for the vehicle to meet, otherwise, the success of the rover mission will be jeopardized. As for each individual

characteristic, the temperature range and lunar surface have already been explained as has the importance of terrain and obstacle negotiation.

The environmental resistance relates survivability to the final characteristic set, mechanical reliability. Characteristics in this set are one-year-life, no maintenance and mechanical reliability. Again, each of these is interdependent to a degree. The environmental resistance will increase the odds of survivability and mechanical reliability. This will increase the chance of the vehicle operating for one year.

Once the characteristics were determined, they were weighted on the order of importance. The weight scale was 0 to 9, 9 being the most important. Below is a list of the characteristics and their weights.

I. Physical Characteristics	Weight
A. Lightweight	9
B. Small size	9
C. Single person deployable	2
II. Design Simplicity	
A. Few parts	4
B. Few moving parts	6
C. Ease of manufacture	3
D. Autonomous	7
III. Survivability	
A. Wide temperature range	9
B. Impact resistance	7
C. Environmental resistance	6
D. Negotiate Terrain	9
E. Negotiate Obstacles	6
IV. Mechanical Reliability	
A. No maintenance	8
B. One-year life	6
C. Mechanical Reliability	9

The evaluation of the morphological study on these weighted characteristics led to four concepts: a legged vehicle, tank vehicle, four-wheel vehicle, and a two-wheel vehicle. The legged vehicle consists of six legs with spiked feet that maneuvers by alternating legs, and it has a solid body and a roll cage for righting itself. The advantage of this design is its ability to negotiate terrain and obstacles easily.

The tank vehicle consists of two tank tracks, where the track will provide the traction for the unit. The unit has independent drive for maneuvering, a solid body and would operate symmetrically. Advantages of this design are its ease of manufacture, mechanical reliability, lightweight, and its ability to negotiate terrain and obstacles.

The four-wheel design has four deep tread tires, and like the tank, it maneuvers with independent drive, has a solid body and operates symmetrically. Its advantages, like the tank, are reliability, lightweight, easy of manufacture and the ability to negotiate terrain and obstacles.

The fourth concept is the two-wheel unit. This has two deep tread tires, and like the two previous concepts, has independent drive, a solid body and operates symmetrically. Advantages of this design include fewer parts, fewer moving parts and lightweight.

Evaluation

To evaluate the best concept, another set of characteristics was determined and weighted. A majority of the characteristics used in the evaluation were used in the concept building as well. The weighted characteristics, forming the design matrix, are shown in Figure 8. The characteristic is graded with a plus, minus or zero, if it is an advantage, disadvantage or neither, with the two-wheel rover as an arbitrary datum. As shown by the completed matrix, the best designs are the tank

and the four-wheel units. These two negotiate the terrain better and have a higher mechanical reliability than the other two. The two-wheel unit will incur durability problems as one portion of it is always dragging. The legged unit has too many parts and will be subject to increased breakdown which results in decreased reliability.

Customer Characteristics	Weight	legged	Concepts tank	four-wheel	Datum two-wheel
No. of Parts	1	-	-	-	0
No. of moving parts	2	-	-	-	0
Ease of Manufacture	2	-	0	0	0
Mechanical Reliability	3	-	0	0	0
Negotiate Terrain	3	0	+	+	0
Negotiate Obstacles	2	0	+	0	0
Traction	1	+	+	+	0
Cost	2	-	0	0	0
Availability of Parts	1	0	0	0	0
Durability	3	-	+	+	0
Weighted Results		-12	6	4	0

Figure 8. Evaluation matrix.

Detailed Design

Overall Concept Description

We designed the lunar rover to be lightweight, compact, and durable. Our design incorporates a composite body aluminum/foam sandwich structure and an external chain and sprocket drive mechanism. The rover's overall weight without the sensor package is 16 lb_m. Our symmetric design allows the vehicle to operate on either side with a ground clearance of 1.50 in. Hemispheres, which are constructed of a carbon reinforced epoxy composite material, are attached to the outer surfaces of the sprockets to prevent the rover from balancing on its side.

The rover platform will be able to support and protect the sensor package which performs the search functions on the lunar surface. Our design concept avoids obstacles by climbing over, going around, or reversing and turning away from them. We incorporated a tank-track style locomotion system to decrease ground pressure, which improves ground clearance, and to increase traction surface area.

The tracks consist of two roller cable chains that are joined by cross members. These cross members will be made of small aluminum channel stock and be attached to the chain so that the channel faces out for traction purposes. A tensioning system will be used to apply the proper tension to the tracks at manufacture, due to the construction of the tracks they should not stretch under most situations.

The outer surface is made of polished and anodized aluminum and will reflect more radiation than it absorbs. This will reduce the amount of heat transferred to the internal mechanisms and electronics of the rover.

Figure 9 shows the tank-track style autonomous lunar rover that was chosen as the final concept.

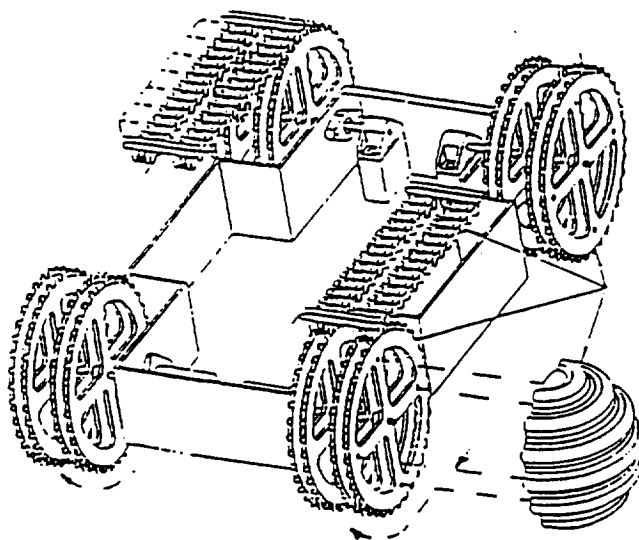


Figure 9. Tank-track style autonomous lunar rover.

Structural Frame and Body

The body of the rover acts as an external frame and all of the components are mounted directly on to it. The body is made of composite plates. The composite structural plates consist of a foam core sandwiched between aluminum sheets. The aluminum sheets are bonded to the foam core with epoxy. The foam core that we have specified is Divinycell HT 110 with a density of 7.0 lb/ft³. The system of plates also allows for easier construction of the rover. The joints between the plate pieces are sealed and bolted for strength and to protect the internals of the rover from the lunar environment. The body is built up from the bottom plate to the top. The internal components mount directly to the bottom plate and then the side plates are added. The top plate adds rigidity to the body package.

Control System

Functions

The control system design serves two functions in controlling the rover. The first feature enables the rover to operate symmetrically, such that it has no top or bottom, only a front and a rear. The controller senses the orientation of the rover and switches the polarity of the drive motors to maintain a forward direction. For example, if the rover was initially traveling forward and somehow became inverted, the motors will reverse direction, and the rover will continue going forward.

The second feature allows the rover to avoid obstacles. The system senses when the rover is encountering resistance traveling forward, then guides the rover back and away in another direction. The assumption here is that the rover went forward into an obstacle and backing away will remove the rover from the problem. Since the forward direction is no longer a safe or valid path, the controller turns the rover to the left by some set angle, and proceeds forward again on a new path.

Design

The control system has four components: the current sensor, a sequential state machine, output selection, and polarity switching. Together, they perform the features described above.

The current sensing component works on the principle that the slower a DC motor turns, the more current it draws. In the rover, the motor will slow when it is obstructed or negotiating an incline. The current passing through the motor also passes through a set of resistors such that the voltage drop across the resistors is proportional to the current. An operational amplifier converts the voltage drop to an amplified signal. This signal will be relative to the amount of difficulty the rover is experiencing traveling forward. This signal is compared to an adjustable reference voltage, or threshold, by a low power comparator circuit. If the signal is greater than the threshold, then the comparator outputs a "high" or +5V signal, otherwise the output is "low" or +0.2V. The final stage of the component checks the current sensor on each side. If either sensor is "high", then it sends a "high" signal to the sequential state machine.

The sequential state machine, as seen in Figure 10 and 11 is a discrete digital system that sequences from state to state at a rate set by the internal clock.

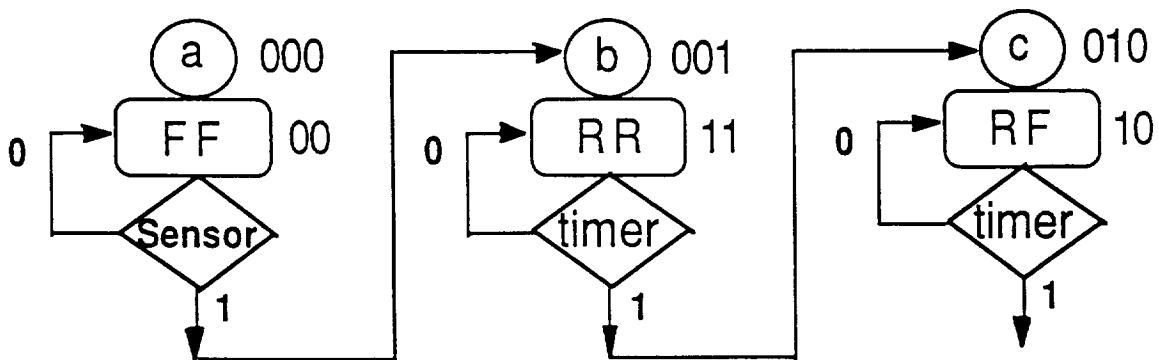


Figure 10. State Machine Diagram.

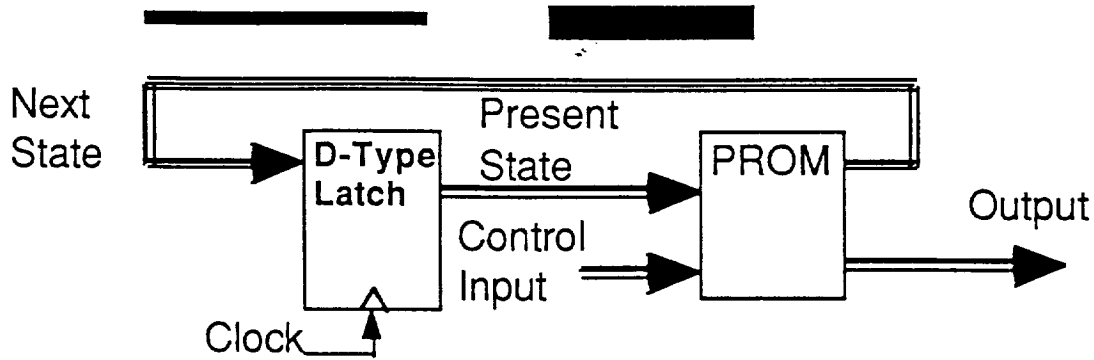


Figure 11. State Machine Block Diagram.

For a three-bit state machine, such as used in this design, each state is labeled with a three digit binary number PS. Each state is associated with a specific binary output word OUT and a next state word NS. The next state value depends on the control input word X_n .

As the state machine sequences, it takes the present state information PS, selects a control input X_n by the multiplexer, and forms input word. The input word is supplied to a programmable read-only memory (PROM) IC as an address. The output word of the PROM is the next state and the its output. For example, if the present state is {000}, its output is {00}, which corresponds to both motor running forward. The control input X_n (in this case, the sensor) will determine whether the next state is {000} or {001} by the input of 0 or 1, respectively.

The outputs from the state machine L and R control the motion of the vehicle, but there are two cases where this output will need to change. The first is when the vehicle inverts, engaging the mercury switch. In this instance, the output from the state machine will have to invert, i.e. a 0 becomes a 1, and a 1 becomes a 0. This reverses the direction of the drive motors to keep the inverted vehicle moving forward. The second case is when the sensor package needs to override the state machine and steer the vehicle according to some other control system (command control).

This modification in the output is done by adding a dual 4-to-1 multiplexer. The switching lines are connected to the mercury switch and the command control enable input. When the mercury switch is closed {1}, the multiplexer selects the inverted L and R controls. When the enable line is asserted {1}, the multiplexer selects the control lines from some other controller. The outputs of the multiplexer go to the polarity switching circuit.

Switching the polarity of the motors with a digital input can be accomplished by two methods. First, there exists a motor driver IC that uses TTL inputs to switch the direction of small DC motors (1A, 36V). The design would require one of these for each motor. The disadvantages to using this IC is it dissipates large amounts of power, may not operate up to 150°C, and limits the size of the motor. The second method is to drive a sensitive double-pole double-throw relay with an operational amplifier. But, there is the chance that the relay will draw too much current and stress the op amp beyond its limits.

Drive Train and Tracks

The rover is driven by an external track system consisting of two separate tracks. The two tracks run independent of one another which allows the vehicle to turn when the tracks rotate at different velocities. Each track is driven and guided by sprocket sets in the front and rear of the vehicle. The sprocket sets rotate on shafts which are in fixed positions coming out of the vehicle's body. Only the rear sprocket sets are driven by the vehicle's motors, while the front sprocket sets are idle and act as tensioning guides. The rear shafts are directly driven by the motors eliminating gear trains where frictional losses could occur. The vehicle is designed so that, regardless of which side of the vehicle is up, the rear sprockets are always driving the tracks. This allows the part of the tracks in contact with the ground to be

in tension which optimizes their performance. The sections which follow discuss each component of the drive system in more detail.

Electric Motors

Motors with the required specifications were not found readily available. The motors will need to meet the requirements listed below, and will likely have to be custom built.

- 12 Volt D.C.
- 1 Amp. maximum current.
- 96 oz.-in. torque output.
- 2.5 in. maximum length.
- 2.25 in. maximum diameter.
- Capable of operating in a vacuum.
- Operating temperature range of -157° to $+121^{\circ}$ Celsius.
- Minimum rated life: 9000 hours.
- Output speed: 5 RPM
- 0.375 in. diameter shafts 3 in. in length

The motors are rigidly attached to the inside of the body on motor mounts which are fixed to the body's lower plate and are also attached to the sidewalls of the vehicle. The output shafts of the motor directly drive the rear sprockets and must, therefore, output the designed sprocket speed of 5 RPM.

Shafts and bearings

The front shafts specified in the design are made of ground 303 Stainless Steel and are 0.375" in diameter. Calculations were made to find stresses in the shafts under static and impact loading situations. The two front shafts and the two motor shafts pass through wall-mounted bearing assemblies, as shown in Figure 13, which are positioned on the inner side walls of the body. These assemblies consist of exterior bearing mounting plates with internal bronze bushings. The front shafts are also internally supported by pillow block assemblies, in addition to the wall-mounted bearings. The two pillow block assemblies sit on top of supports which line them up with the shaft centerline. These supports are mounted to the

lower plates of the vehicle's body in the same fashion as the motor mounts. The pillow block assemblies consist of a support block which also contains bronze bushings.

Sprockets

The sprockets which drive the tracks are shown in figure 14. The sprockets are made of aluminum and have 36 teeth with a pitch diameter of 5.73". Each sprocket has a hub with a set screw and a key way for connecting it to the shaft. Because the track consists of two chains running parallel to one another, there are two of these sprockets on each shaft. These sprockets must be lined up so that corresponding teeth are in the same angular position in order for the track to run smoothly.

Tracks

An illustration of a section of the vehicle's track and the components which comprise it are shown in Figure 12. Each track consists of two roller-cable chains which are connected by cross pieces acting as the traction. The advantage to this type of a chain is that the links are not in sliding contact with one another requiring

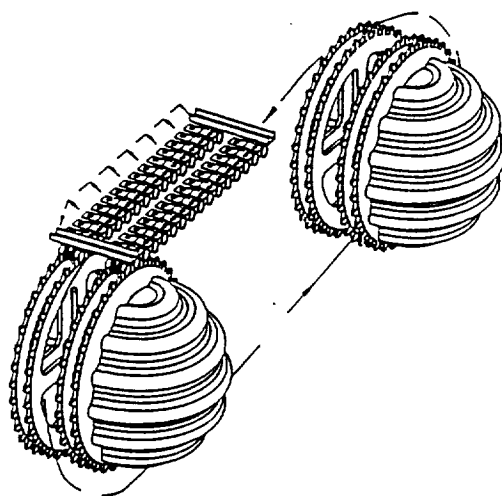
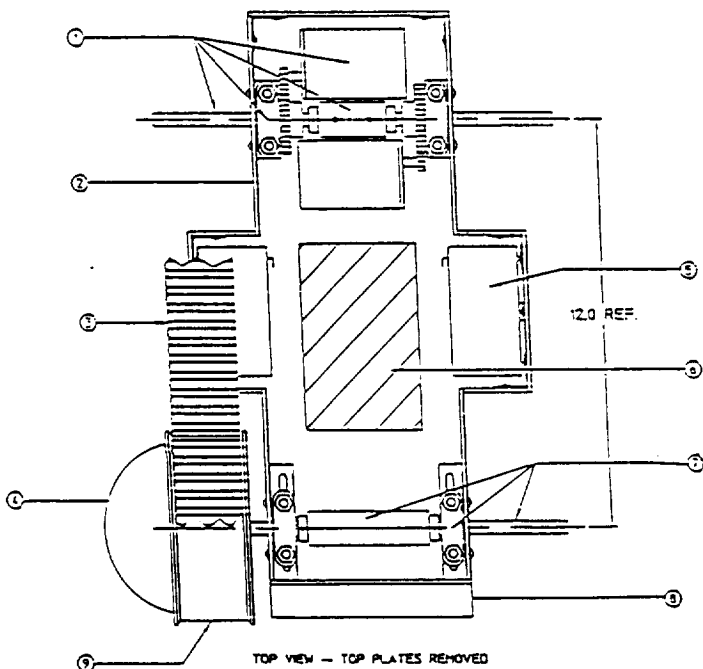


Figure 12. Track assembly and components.

no lubrication. Each roller link consists of a stainless steel pin capped with molded Teflon rollers that are centered on the cable. The cable itself is made of braided stainless steel 1/16" in diameter. Aluminum brackets are included on the roller links which act as mounting plates for the cross members. The cross members are aluminum U-channel stock and are mounted on every other bracket with the open channel facing out from the track.

Prototype

To facilitate testing and to gain some insight as to what some of the problems might be for the Lunar Rover on the moon, the Spring senior design group built a prototype of the lunar rover design (see Figure 13). This prototype was to use the same basic design of the lunar rover, but not necessarily be made of the same materials and subparts. Since approximately only \$1400 had been allocated, the materials and parts selected had to be relatively inexpensive and easy to locate. The following pages will explain how the prototype was built and what materials were used in the process.



9	4	TRACK BELT DRIVE PULLEY
8	1	FRONT STYROFOAM DOME - 12" TALL x 7" DEEP ATTACHED TO BODY USING 2-TON EPXY
7	1	FRONT SHAFT/SUPPORT SUBASSEMBLY
6	1	ELECTRONIC CONTROL CIRCUIT
5	2	PANASONIC 12V LEAD-ACID RECHARGABLE BATTERY
4	4	5" DIA. STYROFOAM DOME - 7" DEEP ATTACHED TO BODY USING 2-TON EPXY
3	2	DOUBLE SIDED 1/2" TIMING BELT WASHINGTON #2.5" 1 DRIVE SYSTEMS - CATALOG B
2	1	MAIN BODY STRUCTURE SUBASSEMBLY
1	1	REAR DRIVE SYSTEM SUBASSEMBLY
ITEM	QTY.	DESCRIPTION

Figure 13. Autonomous Lunar Rover Prototype; top view.

Initially, the main concern in building the prototype was to find a DC motor that would give good performance parameters, yet be small and light enough for the prototype body. The main performance criteria was that the prototype should be able to climb up a 45° incline without stalling and reversing. After performing some torque calculations, we determined that approximately 200 oz-in of torque per side would be sufficient to drive a 26 lb_m prototype rover.

The prototype was primarily made of aluminum. Aluminum pillow blocks that support the bearings for the shafts were installed at each corner of the rover. These blocks were used to attach the side pieces of the rover to the bottom plate. The motors were installed into motor mounts that were attached to the bottom plate of the prototype.

The wheels of the prototype were machined from 6" diameter aluminum stock. Double-sided timing belts 42" long were used for the track instead of the chain system. The prototype was assembled with L-brackets and pop-rivets at the joints that weren't already attached by screws to the pillow blocks. The top plate is attached to the prototype with four screws. Holes were drilled into the bottom plate to mount the circuit packages. The two lead-zinc batteries are mounted into the sides of the prototype with double-sided carpet tape. The final weight of the prototype is 20 lb_m.

Conclusions

Prototype Performance

On the rover's initial run, it climbed a grass hill at a slope of about 40°. The mercury switch circuit successfully reversed both motors when the rover was flipped over. The rover climbed up a steeper slope on a loose dirt surface, and

later ran down some concrete steps. Basically, the prototype could climb steep inclines on various surfaces, withstand minor impacts, and continue functioning properly when flipped over. The current sensing circuit never operated to properly start the state machine routine. The main problem with the circuitry was that they couldn't receive a regulated voltage and current while in the rover. The circuits worked fine on the breadboards when they had a regulated power supply, but competed for power when combined with the other components.

Recommendations

Our main recommendation is to have further consulting and more extensive testing performed on the control circuit. It may be better to use a mechanical switch rather than the mercury switch due to the extremes of the lunar environment. More extensive research should be performed in order to confirm that our specified materials will survive the environmental extremes. A material likely exists that could be used for a single piece, continuous, flexible track similar to that used on the prototype. If this material is located, it would greatly simplify the current two chain track design. Also, an active tensioning system should be designed for the tracks. This would allow the tracks to be automatically adjusted to a set tension whenever they expanded or contracted due to temperature changes or stretched due to extended use. Further work should be done on the heat transfer problem to determine a way to cool the rover. If the internal temperatures experienced in the rover could be lowered it would increase the reliability of the components.

Overall Conclusions

Using the Quality Function Deployment method of design, the senior design class from each semesters developed a small micro-rover based on separate customer requirements. The first semesters project for the MESUR mission

provided a simple, lightweight and reliable machine that accomplished the requirements of the customer of obtaining a sample of a rock on the surface of Mars. It also achieved an important desire of the customer in that it can obtain multiple samples at each site. This feature adds a great value to the MESUR mission with minimal costs. The second semesters Autonomous Lunar Rover is capable of reliably transporting a sensor across the surface of the Moon gathering important information. The development of prototypes of these designs showed the success in achieving their goals.

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Appendix A

Overview of Quality Function Deployment (QFD) Methods

The design method use by the design team is referred to as the QFD (Quality Function Deployment) method. The QFD method is a step by step design method that ensures a complete and robust design. The QFD steps are outlined below.

- Construct House of Quality
 - Define customer attributes.
 - Set engineering characteristics and values.
 - Assign weights to customer attributes.
 - Measure the effect of the engineering characteristics on the customer attributes.

- Develop Function Outline
 - The function outline lists all functions the design needs to satisfy.

- Function Morphology
 - The function morphology assigns several concepts to each function.

- Conceptual Design Ideas
 - Function concepts from the function morphology are combined into several overall conceptual ideas.

- Datum Comparison
 - One of the overall concepts is assigned as a Datum, the other concepts are compared against this Datum.

 - The design that compares the best against the Datum is picked as the concept that will be developed into the final design.

Located on the following pages of this appendix are the results the design group achieved for each of the QFD steps (except the function outline which is located within the report text).

- X - Strongly Effects
- X - Effects
- X - Slightly Effects

Customer Attributes

Physical Attributes	Light Weight
	Fit Inside Lander Ports
Design Simplicity	Low Wind Resistance
	Reliable
	Min. # of Movements
	Min. # of Parts
	Inexpensive
	Minimum Human Interaction
	Temperature Resistance
	Wide Operating Temp. Range
	Impact Resistance
	Environment Resistance
Survivability	Long Life Cycle
	Independent of Lander Position
Deployment & Sampling Requirements	Contact Detector With Sensor
	Reasonable Deployment Time
	Obtain Sample
Power Requirements	Low Power Requirements
	Standard Voltage Capability
Communication & Data Sampling Requirements	Uses Lander Comm. Syst
	Standard Data Acquisition Rate

Relative Importance

Engineering Characteristics

10 kg	9	X	X		Mass
70 ccm	9	X	X		Size
< 3 Months	9	X	X		Manufacturing Time Required
125	9	X	X		Safety Factor > 1
40 g	9	X	X		Max Allowable Impact
10 N	9	X	X		Attachment Force Required
3 Max	9	X	X		Number of Degrees of Freedom
> 50	9	X	X		Number of Moving Parts
2nd order	9	X	X		Order of Control
1 micron	9	X	X		Dust Seal Resistance
> 1 m	9	X	X		Max. Placement Distance
160 degrees	9	X	X	X	Operating Envelope r
90 degrees	9	X	X	X	Operating Envelope theta
> 12 watts	9	X	X	X	Operating Envelope phi
6 Watts	9	X	X	X	Peak Power Required
115 volts	9	X	X	X	Average Operating Power
> \$10,000	9	X	X	X	Standard Voltage of Lander RTG
35 degrees C	9	X	X	X	Cost
-160 Degrees C	9	X	X	X	Max. Operating Temp.
316 degrees C	9	X	X	X	Min. Operating Temp.
	9	X	X	X	Entry Temp.
	9	X	X	X	Communication Power Required
	9	X	X	X	Communication Response Time
	9	X	X	X	Data Sampling Rate

MESUR PROJECT MORPHOLOGY

FUNCTIONS	POSSIBLE SOLUTIONS						
1.2.1 Hold	latch	strap	self locking	graple	enclosed	pyrospring	
2.1 Seperate instrument from lander							
.1 Initialize	inertia actuated						
.2 Energize	spark	solenoid	relay				
.3 Find exit path	camera	mercury switch	sensor prod	gravity orienting	light sensor		
.4 "Escape" from lander	pyro-spring	robot arm	rail-gun	catapult	stair		
	roll out	rack & pinion	move lander	belt drive			
2.2 Upright instrument (if needed)							
.1 Determine uprightnes	camera	mercury switch	sensor prod				
.2 Upright	self righting	yank tether	robot arm	independent robot			
.3 Check uprightnes	see 2.2.1						
2.3 Initial positioning (assuming that we move the apx)							
.1 Locate sample	camera	dig	sensor prod				
.2 Adjust orientation	arm	robot	self orienting				
.3 Move to sample	tether drag	robot arm	rail gun	self propelled	independent robot		
- for arm :		telescope	fold out	scissor	ribbon		
3.1 Prepare sample							
.1 Secure to rock	graple	screw into	butt against	adhesive			
.2 Remove brine	drill	grind	break	scrape	chisle	etch	pry
	explode						
3.2 Make contact							
.1 Remove prep equip.—	turn	push	pull	raise	drop		
or Remove sample—	scoop	auger	suction shavings	sweep	dump	lift rock	

3.2 Make contact				
.2 Put sample into apx or	dump	auger shavings	sweep	suction drop rock
Orient apx on sample	arm	robot	self orienting	

note: This assumes that the apx does need to be deployed
 Without apx deployment, functions 2.1 - 2.2 can be ignored.

Appendix B
MESUR Tubular Deployment System (TDS) Calculations

Stress Calculations

The critical point in the design of the Tubular Deployment System was observed to be at the interface between the Outer and Middle Tubes. If this interface was to fail, the TDS would only perform the function of raising the APX Walker out of the lander if the system was upside down (with respect to the APX Walker). This junction therefore must be able to withstand the 40g impact that will occur when the lander reaches the Martian surface.

The interface was evaluated at four points:

Lower Flange
Middle Tube
Upper Flange
Outer Tube

The mass that was used in the calculations was the mass of all components enclosed by but not including the outer tube. The total mass of these components was calculated to be 2.335 kg.

The gravity on Mars is one-third that of Earth's gravity, so the acceleration of gravity used in the calculations is 3.27 m/s².

The force exerted on the interface due to static loading is:

$$F = m \cdot g = 2.335 \cdot 3.27 = 7.636 \text{ N}$$

Evaluating at the four points:

Lower Flange:

The major stress in this component is a result of bending action on the flange. Therefore, the stress in the flange is given by:

$$\sigma_{st} = \frac{My}{I}$$

Where: $I = bh^3/12$ $M = F \cdot (\text{moment arm})$

for the flange: $b = 0.0135$ $h = 0.006$ $y = 0.003$ moment arm = 0.02

Therefore: $I = 2.43 \times 10^{-10} \text{ m}^4$

Solving:

$$\sigma_{st} = 1.8855 \text{ MPa}$$

Taking the impact into account:

$$\sigma_I = 40 \quad \sigma_{st} = 75.418 \text{ MPa}$$

The yield strength of 2024 T4 Aluminum is 323 MPa. Assuming failure in shear, the critical stress is 161.5 MPa. The factor of safety, considering impact, is therefore:

$$n = 161.5 / 75.418 = 2.14$$

So the flange will withstand the impact.

Middle tube:

For the stress calculation in this component, bending effect was assumed to be negligible due to the added rigidity from the whole tube, not just the section that the flange is connected to.

Using the axial stress equation:

$$\sigma_{st} = \frac{F}{A}$$

Where F is the static force and A is the area covered by the flange, assuming a perfect connection between the flange and the tube.

Taking $A = 2 \cdot (0.01) \cdot (0.002)$ (twice the length times the wall thickness)

$$\sigma_{st} = 1.909 \times 10^5 \text{ Pa}$$

With impact:

$$\sigma_I = 7.636 \text{ Mpa}$$

Ultimate strength of PVC is 50 MPa

Factor of Safety:

$$n = 50 / 7.636 = 6.55$$

Middle tube will withstand the impact.

Upper flange:

The configuration of the Upper Flange is such that it is difficult to calculate the stresses directly. The flange consists of a flat piece of sheet aluminum that is radiused to match the curvature of the Outer Tube. The Flange is connected to the tube through the use of three tabs. The method used was to project a fraction (75%) of the area of the tube covered by the two outside tabs onto the same plane of the area covered by the middle tab, resulting in a working dimension to be used for a bending stress in the upper flange.

The resulting cross-section has the dimensions:

$$b = 0.03634 \quad h = 0.002 \quad y = 0.001$$

Here $I = 2.4227 \times 10^{-11} \text{ m}^4$

Using the bending stress as in the previous bending stress calculation,

$$\sigma_{st} = 2.68 \text{ MPa}$$

Taking the 40g impact into account,

$$\sigma_1 = 107.16 \text{ MPa}$$

The resulting factor of safety (assuming shear failure):

$$n = 161.5/107.16 = 1.50$$

Therefore the Upper Flange will withstand the impact.

Outer Tube:

As in the case of the Middle Tube, bending stress is considered negligible due to the fact that the tube has rigid support from the adjoining material not covered by the Upper Flange.

Axial stress is calculated:

With three tabs, the Upper Flange covers 60 mm along the edge. Thus the area covered is:

$$A = (0.06) \cdot (0.002) = 1.2 \times 10^{-4} \text{ m}^2$$

The force again is:

$$F = 7.636 \text{ N}$$

Static stress:

$$\sigma_{st} = 7.636/1.2 \times 10^{-4}$$

$$\sigma_{st} = 6.3633 \times 10^4 \text{ Pa}$$

For 40g impact:

$$\sigma_1 = 2.545 \text{ MPa}$$

Factor of safety:

$$n = 50/2.545 = 19$$

The Outer Tube will withstand the impact.

Motor Requirements

The maximum load on the TDS motor will occur if the Lander comes to rest "upside down" on the Martian surface (when both the Inner and Middle Tubes will need to be deployed to get the APX Walker out of the Lander).

This maximum load is derived from the mass of the parts that will be moved times the acceleration of gravity on Mars. The components involved in this calculation are all the components enclosed by, but not including the outer tube. The mass of these components was calculated to be 2.3352 kg (including the APX Walker).

Therefore, the resistive force is :

$$F = mg = 2.3352 * (3.27) = 7.636 \text{ N}$$

This force is carried over both pulleys, and onto the winding spool.

The torque needed to move the TDS is then the resistive force times the maximum moment arm, taken from the center of the shaft to the outermost winding on the cable.

The outermost winding distance from the center of the shaft = 20 mm = 0.020 m

So: $T = F * d = 7.636 * 0.020 = 0.1572 \text{ N-m}$

Converting to oz.-in.:

$$T = 0.1572 \text{ N-m} * (141.6 \text{ oz.-in./N-m})$$

$$T = 22.26 \text{ oz.-in.}$$

Appendix C
MESUR Mass Calculations

TDS Mass Calculations

Component	Volume (m ³)	Material	Mass (kg)	Quantity
Inner Tube	2.66 X 10 ⁻⁴	Rigid PVC	2.21 X 10 ⁻¹	1
Middle Tube	3.09 X 10 ⁻⁴	PVC	2.57 X 10 ⁻¹	1
Outer Tube	4.71 X 10 ⁻⁴	PVC	3.91 X 10 ⁻¹	1
Runner	1.02 X 10 ⁻⁵	PVC	8.47 X 10 ⁻³	12
Inner Caps	1.33 X 10 ⁻⁵	2024 T4 Al	3.59 X 10 ⁻²	2
Middle Cap	1.80 X 10 ⁻⁵	Al	4.86 X 10 ⁻²	1
Spool	5.10 X 10 ⁻⁶	Al	1.38 X 10 ⁻²	1
Shaft	4.00 X 10 ⁻⁷	Al	1.08 X 10 ⁻³	2
Cable Clamp	1.60 X 10 ⁻⁶	Al	4.32 X 10 ⁻³	1
Motor Mount	3.90 X 10 ⁻⁶	Al	1.05 X 10 ⁻²	1
Mounting Flange	4.10 X 10 ⁻⁶	Al	1.11 X 10 ⁻²	1
End Plug	2.30 X 10 ⁻⁶	Al	6.21 X 10 ⁻³	2
Support Tubing	4.35 X 10 ⁻⁵	Al	1.18 X 10 ⁻¹	1
Lower Flange	2.01 X 10 ⁻⁴	Al	5.41 X 10 ⁻¹	1
Upper Flange	1.30 X 10 ⁻⁶	Al	3.51 X 10 ⁻³	1
Pulley	1.60 X 10 ⁻⁶	Nylon	1.76 X 10 ⁻³	2
Motor	-----	-----	1.50 X 10 ⁻¹	1
			Total =	1.96 kg

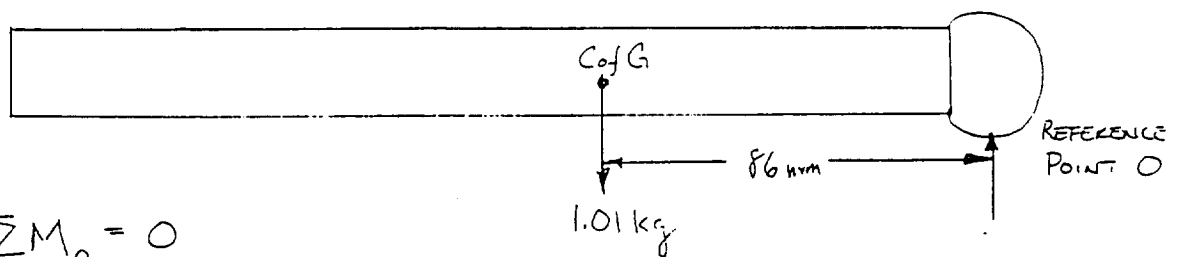
Note:

Densities of materials are as follows:

Rigid PVC = 830 kg/m³
 2024 T4 Al 0 2700 kg/m³
 Nylon = 1100 kg/m³

Mass Break-Down of APX Walker		
Component Name	Mass (kg)	Center of Gravity (From the Reference)
APX/Grinder Assembly	0.20	164 mm
Drive Motors	0.35	110 mm
Body Assembly	0.12	130 mm
Tether Assembly	0.34	0 mm
Totals	1.01	86 mm

Using a Moment Balance on the APX Walker, the center of gravity was calculated. These calculations are shown below.



$$(+ \sum M_o = 0$$

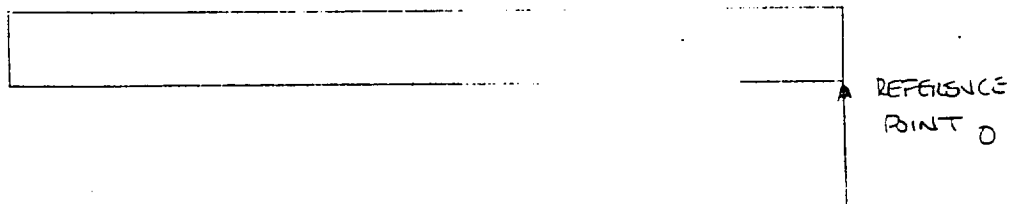
$$(\text{TOTAL MASS})(\text{CENTERS OF G}) = (\text{APX/GRINDER})(\text{Cof G}) + (\text{DRIVE MOTORS})(\text{CENTERS OF G}) + (\text{BODY})(\text{CENTERS OF G}) + (\text{TETHER})(\text{CENTERS OF G})$$

$$\text{CENTER OF GRAVITY} = \frac{(0.2 \text{ kg})(164 \text{ mm}) + (0.35)(110 \text{ mm}) + (.12)(130 \text{ mm}) + (0)}{(1.01 \text{ kg})}$$

$$\text{CENTER OF GRAVITY} = \underline{\underline{86 \text{ mm}}}$$

Mass Break-Down for Body Assembly		
Part Name	Mass (kg)	Center of Gravity (From the Reference)
Outside C-channel	0.0504	97.5 mm
APX C-channel	0.0192	154 mm
APX Cross Rib	0.0098	112.5 mm
Front I-Beam	0.0038	145 mm
Middle I-Beam	0.0167	87.5 mm
Rear C-Channel	0.0101	20 mm
Front Covers	0.0034	195 mm
Mounting Block	0.0095	100 mm
Totals	0.1223	120 mm

Using a Moment Balance on the Body Assembly Parts, the center of gravity of the Body Assembly was calculated. These calculations are shown below.



$$\sum M_o = 0$$

$$\begin{aligned}
 (\text{TOTAL MASS})(\text{CENTER OF GRAVITY}) &= (\text{OUTSIDE CHANNEL})(\text{CofG}) + (\text{APX-CHANNEL})(\text{CofG}) \\
 &+ (\text{APX CROSS})(\text{CofG}) + (\text{FRONT I-BEAM})(\text{CofG}) \\
 &+ (\text{MID I-BEAM})(\text{CofG}) + (\text{REAR CHANNEL})(\text{CofG}) \\
 &+ (\text{FRONT COVERS})(\text{CofG}) + (\text{MOUNT BLOCK})(\text{CofG})
 \end{aligned}$$

$$\begin{aligned}
 \text{Body} \\
 (0.1223 \text{ kg})(\text{CENTER OF GRAVITY}) &= (0.0504 \text{ kg})(97.5 \text{ mm}) + (0.0192)(154 \text{ mm}) + (0.0098)(112.5 \text{ mm}) \\
 &+ (0.0038 \text{ kg})(145 \text{ mm}) + (0.0167 \text{ kg})(87.5 \text{ mm}) + \\
 &+ (0.0101 \text{ kg})(20 \text{ mm}) + (0.0034 \text{ kg})(195 \text{ mm}) \\
 &+ (0.0095 \text{ kg})(100 \text{ mm})
 \end{aligned}$$

$$\text{CENTER OF GRAVITY} = \frac{14.63 \text{ kg} \cdot \text{mm}}{0.1223 \text{ kg}} = 120 \text{ mm}$$

The table below lists, briefly describes, and gives the weight of each component of the APX/Grinder Assembly. Details such as dimensions and manufacturing are given in the final drawings.

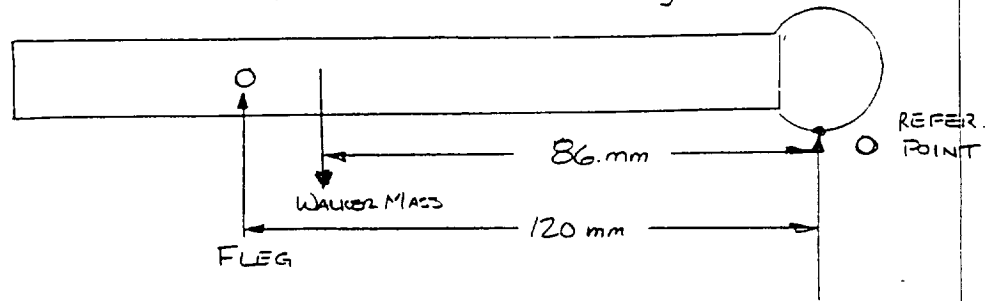
Component	Description	Quantity	Mass Each	Mass Total
Motor	12 V, 1 Amp	One	30 Grams	30 Grams
APX/Motor Cage	Encloses APX And Motor	One	35 Grams	35 Grams
APX	Elemental Inst.	One	75 Grams	75 Grams
Axles	Rotation Shaft for APX/Grinder	Two	2.5 Grams	5 Grams
Solenoids	To engage gear & hold position	Two	10 Grams	20 Grams
Mounting blocks	Mount APX/Grind. to Walker Body	Two	5 Grams	10 Grams
Front Beveled Gear	Mounted to grinding disk	One	10 Grams	10 Grams
Side Beveled Gear	Allow Assem. to Rotate	One	20 Grams	20 Grams
Total Mass				205 GRAMS

Mass Break-Down for Tether Assembly		
Part Name	Mass (kg)	Description
Body	0.04	1500 mm ³
Tether	0.05	4 m of 28 gauge stranded copper wire
Spool	0.05	Machined Lexan
Gears & Shafts	0.01	-----
Wheels	0.14	Aluminum
Worm Gear and Follower	0.05	-----
Total	0.34	-----

Appendix D
MESUR Motor Torque Calculations

TORQUE CALCULATIONS FOR DRIVE MOTORS

ASSUME: All of WALKER MASS IS SUPPORTED BY ONE LEG



$$\text{WALKER MASS} = 0.80 \text{ kg}$$

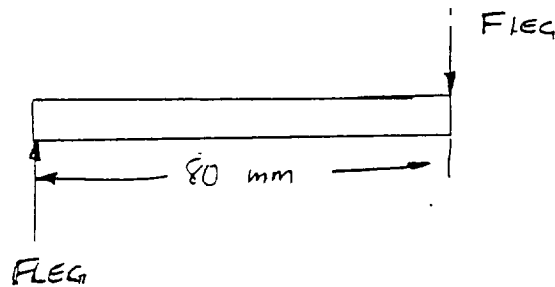
$(+\sum M_o = 0)$ MOMENT BALANCE TO FIND FLEG.

$$86 \text{ mm} (1.01 \text{ kg}) - (\text{FLEG}) (120 \text{ mm}) = 0$$

$$\text{FLEG} = 0.724 \text{ kg} + (3.27 \text{ m/s}^2) = 2.37 \text{ N}$$

$$\text{MARSHALL GRAVITY} = \frac{9.81 \text{ m/s}^2}{3}$$

FORCE SEEN ON WALKER LEG



FORCE ON LEG CAUSES A COUPLED MOMENT REQUIRING A TORQUE.

$$\text{TORQUE} = \text{FLEG} * \text{COUPLE DISTANCE}$$

$$= 80 \text{ mm} * 2.37 \text{ N} = 190 \text{ N} \cdot \text{mm}$$

CONVERSION TO OZ-IN

$$(\text{OZ-IN}) \text{ TORQUE} = \left[\left(\frac{190 \text{ N} \cdot \text{mm}}{1000 \text{ mm/m}} \right) / 0.113 \frac{\text{N} \cdot \text{m}}{\text{lb} \cdot \text{in}} \right] * 16 \frac{\text{oz}}{\text{lb}}$$

$$\text{REQUIRED TORQUE} = \underline{\underline{26.9 \text{ OZ-IN}}} \text{ FOR EACH MOTOR.}$$

* NOTE. THIS FIGURE DOES NOT INCLUDE THE MASS OF THE WALKER LEGS. HOWEVER, THE DESIGN CALLS FOR MOTOR RATED AT 60 OZ-IN.