# PLANETARY SURFACE EXPLORATION
# MESUR/AUTONOMOUS LUNAR ROVER

**University of Idaho**
**Department of Mechanical Engineering**
**Moscow, Idaho**

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

## 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 16 MESUR landers around the turn of the century. A Tubular Deployment System and a spiked-legged walker have 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 that 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.

## Introduction

For the 1991-92 school year, the NASA groups of 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 NASA/Ames Research Center (ARC), Moffet Field, CA. There was a different project with different customer requirements each semester, which led to two different types of micro-rovers accomplishing their particular tasks. Fall semester students worked on a rover for deployment of an instrument to collect data about the surface of Mars, while the Spring semester students developed a rover for exploration of the moon's 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 Fall Mechanical Engineering senior design team was requested on August 27, 1991 to design a deployment system for the instrumentation devices for 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 that will 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: multi-band imaging
- Meteoreology 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, our NASA representative for this project, 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 focuses 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.
- Simple design
  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 that all instrumentation perform during this period.
- 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. Therefore, the outer crust needs to be removed before the APX can be placed on the surface.
- 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.
- Low power usage
  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.
- Resistance 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.
- Orientation independent
  The landers do not experience precise and controlled landings. 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. Using the above requirements from the customer, the functions that needed to be accomplished were developed. The three major functions of the design are 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.
- Location and obtainment of multiple rock samples on the Martian Surface.

Each of these functions was broken down into smaller detailed subfunctions whose requirements could be considered individually.

### Morphology/Concepts/Evaluation

A morphology study was performed to establish a means of accomplishing these functions. 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 was determined that the spiked-legged walker concept fit the requirements best.

## Detailed Design

From this analysis, the final design concept is the APX Deployment System, which has two major components: the Tubular Deployment System (TDS), to hold the instrument in transit and remove it from the lander, and the APX Walker, to move the instrument to a sample, prepare the sample, and collect the data. These two components will interface with the existing landers which are currently being designed by Ames Research Center.

### Tubular Deployment System

This system is designed to secure the APX Walker inside the MESUR lander during transit from Earth to the Martian surface. It interfaces directly with the existing lander design by fitting into one of the allocated instrumentation ports that are located around the lander's circumference. The major requirement of the design is the ability of the system 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) as shown with the APX Walker in Figure 1. The TDS consists of three concentric tubes that enclose the APX Walker and extend out of the lander in a telescoping fashion. The innermost tube holds the APX Walker during travel to Mars and has 140° of material cut out to allow the walker to escape onto the surface. The middle tube is cut out 130° 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.

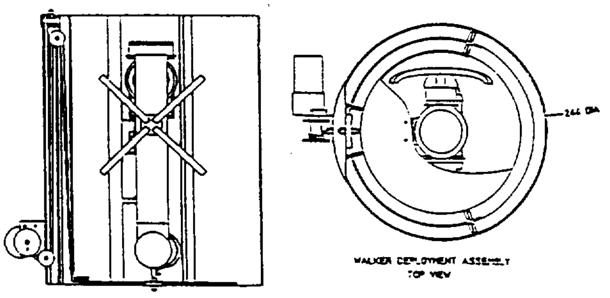


Fig. 1 Tubular Deployment System with APX Walker

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.

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-RPM 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 determine 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.

## 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.

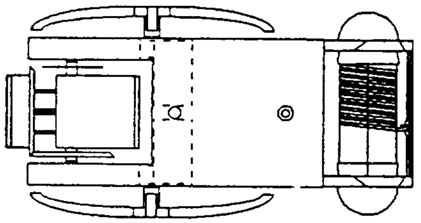


Fig. 2 Top view of APX Walker Assembly

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 2) are positioned behind the APX/Grinder Assembly. The Tether Assembly is located in the rear of the Walker. The side and front views of the APX Walker are shown with the TDS Assembly in Figure 1.

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 bent into an elliptical shape to allow the Walker to flip over more easily if it topples onto its side.

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

Table 1 Physical characteristics of APX Walker

| | |
|---|---|
| Height<br>(with legs)<br>(without legs) | <br>160 mm<br>60 mm |
| Length | 255 mm |
| Width<br>(with legs)<br>(without legs) | <br>144 mm<br>100 mm |
| Approximate mass | 1.01 kg |
| Center of gravity (measured from the rear) | 86 mm |
| Volume displacement<br>(with legs)<br>(without legs) | <br>5875 $cm^3$<br>1530 $cm^3$ |

The APX Walker has the following operational characteristics:

Table 2 Operational characteristics of APX Walker

| | |
|---|---|
| Power requirements (including grinder and drive motors) | 2.5 Watts |
| Maximum speed | 0.3 m/min |
| Turning radius | 80 mm |
| Operating range | approx. 4 m diameter |
| 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 3. This assembly consists of eight separate parts that are joined together with aluminum braze.

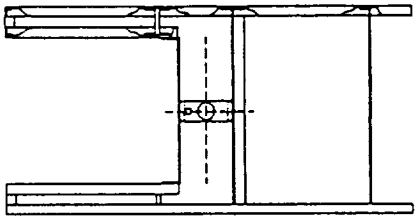


Fig 3 Body Assembly

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 lightweight alloy gives the APX Walker the strength required to hold the three components in the walker and to absorb the impacts it will experience. This material also has reasonable machining characteristics that are needed in forming these parts.

**APX/Grinder Assembly**

The functions that the APX/Grinder Assembly must be able to perform are detailed and listed below:

- Prepare surface
  The brine/crust on the outer surface of the samples needs 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.

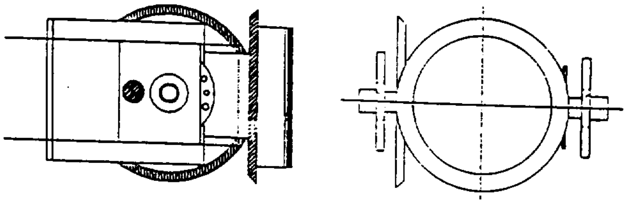
The design concepts of the APX/Grinder Assembly began to develop during the Function Morphology portion of the QFD design method. First, a method of preparing the surface was selected. A disk grinder was chosen for this task for several reasons. A grinder seemed to be the simplest tool for removing the brine (as compared to a belt-driven sander, pneumatic chisel, drill and catch tray, or 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 RPM, low torque electric motor would be used to power the grinder.

The design team then decided that positioning could be done most feasibly by placing the APX and grinder faces 180° apart and rotating the whole subassembly to switch their positions. The rotation method would keep the width to minimum and could be readily accommodated in the APX Walker design.

Additional concepts were developed:

- To keep simple and minimize power requirements and mass, the APX/Grinder Assembly should be able to rotate without requiring another electric motor in addition to the grinder motor.
- The rotation should be controlled so that the assembly will not rotate the APX and the grinder while the grinder is in use.
- Grinding and sampling need to be accomplished from a variety of positions and angles.
- Slight, but constant, pressure should be kept while grinding the sample surface.
- The rotation mechanism should be bi-directional to resist twisting.
- The controls should be integrated with the walker control panel and the lander's imaging system.

The side and front views of the APX/Grinder design are shown in Figure 4 (the top view is in the APX Walker Assembly, Figure 2).



F ig 4 APX/Grinder Assembly

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 long-lasting capability to grind a very smooth surface. One beveled gear is coupled to the backside of the grinder, while the other is located on the axle (around which the entire assembly rotates). 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. The APX and grinder motor are mounted inside a cage for protection. 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.

**Tether Assembly**

Since the MESUR project encompasses seven to nine years, the Tether Assembly was chosen to supply 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 4-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 used only to supply power to the walker, the data from the APX is transmitted back to the lander using radio waves. 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 two meters from the lander.

The tether assembly (shown in Figure 5) has four major parts that include the spool, wheels, worm gear mechanism, and the gears that connect the other three parts. Since it has only four major parts, the tether is simple and reliable. The assembly's mass is 0.34 kg. This amount of mass ensures the wheels and spool remain in contact with surface while the walker is moving.

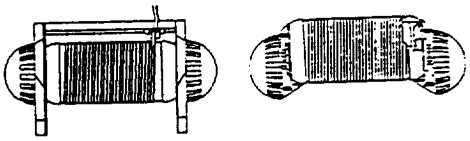


Fig. 5 Tether Assembly

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 roll 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 can turn around on the Martian surface.

## 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. If its range is increased, the walker might be unable to use the lander's imaging system, requiring one of its own.

Since the parameters of the lander are not set, the APX Walker and TDS can be readily scaled up or down 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.

Due to its simplicity and precision, the control 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 that 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 short 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 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

NASA is developing an automated planetary exploration system to search for minerals on distant planets. The system involves deploying many autonomous vehicles to search the surface of a planet randomly 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 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, at least one of the several rovers 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 can be applied on future planetary exploration missions.

### Project Description/Background

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 span. 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: (1) it does not require any contact with humans; (2) it does not require remote directional or intelligent control; (3) it can avoid obstacles; and (4) 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 need a reliable, autonomous vehicle to transport a NASA 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 of human intervention. This type of vehicle is also needed to test the reliability of the design for possible application on other planets.

### 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 reevaluate both concepts with set criteria to determine the better design. This reevaluation of the designs centered around the fundamental difference between the two concepts, to have a wheeled rover or one with tracks.

The reevaluation of the concept started with a literary search. This search revealed Dr. M.G. Bekker's research, which was an intricate part of the lunar roving vehicle design team for the Apollo program; Bekker 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."[3]

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

Bekker[3] demonstrates a method to calculate the tractive force for both wheeled and track vehicles. The tractive force is the force the track or wheel exerts on the ground and is dependent on soil conditions, c and $\phi$, 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:[3]

$$T_n = 4A_{wc} + W\tan(\phi) \text{ (for the wheeled vehicle)}$$

$$Hn = 2A_{tc} + W\tan(\phi) \text{ (for the track vehicle)}$$

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 $\phi$ 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 6 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; therefore, 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 and, consequently, a larger vehicle thrust. The track concept results in larger tractive force and vehicle thrust than the wheel concept. The reevaluation of the design concept and the results of these calculations resulted in the selection of the track over the wheel.

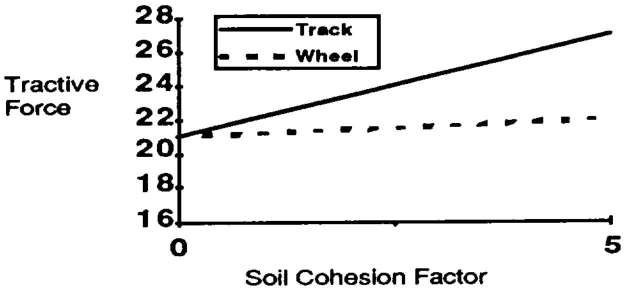


Fig. 6 Tractive force vs. soil cohesion factor[3]

## Design Specifications

Customer desires for the rover and their priority of importance include:

- Able to transport sensor package
- Durable
- One-year life span
- Lightweight
- Able to withstand lunar conditions
- Small
- No maintenance
- Ease of manufacture
- Inexpensive
- Few moving parts

### Engineering Requirements

- Mass less than 20 $lb_m$
- Volume less than 1.0 $ft^3$
- Withstand temperature range -157° C to +121° C
- Operate at gravity equal to 5.32 $ft/s^2$
- Operate at pressure $10^{-13}$ times that of Earth
- Withstand a 30-ft freefall onto 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
- have a 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 or human interaction
- be capable of deployment by a single person

**Want:**

- smaller than 1.0 $ft^3$, 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 with black box)
- packaging for transport
- deployment

## Concept Development

An important step in the lunar roving vehicle design process was the functional decomposition. The functions of the rover can be broken into seven groups: locomotion, traction, sensor support, sensor protection, self-righting ability, obstacle sensing ability, and obstacle negotiation. Once the functions of the rover had been decomposed into smaller subfunctions, the next step was to determine methods for performing each individual function. This step, commonly referred to as the morphological study, involved some minor research and brainstorming for possible methods. In considering design concepts, the group determined and weighted characteristics that were significant in selecting options from the morphology to perform functions. These characteristics fell into four basic groups: physical characteristics, design simplicity, survivability, and mechanical reliability.

Once the characteristics were determined, they were weighted in the order of importance. The evaluation of the morphological study on these weighted characteristics led to four concepts: a legged vehicle, a tank vehicle, a four-wheel vehicle, and a two-wheel vehicle.

To evaluate the best concept, another set of characteristics was determined and weighted. A majority of the characteristics used in the concept building were used in the evaluation as well. The weighted characteristics formed the design matrix. This design matrix showed that 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. A comparison between these two led to the choice of the tank vehicle as the final concept for the Lunar rover.

## Detailed Design

### Overall Concept Description

The lunar rover was designed to be lightweight, compact, and durable. The 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 $lb_m$. The 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. The design concept avoids obstacles by climbing over, going around, or reversing and turning away from them. A tank-track-style locomotion system was incorporated 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 7 shows the final design concept of the tank-track style autonomous lunar rover (without control system and sections of track cut away).

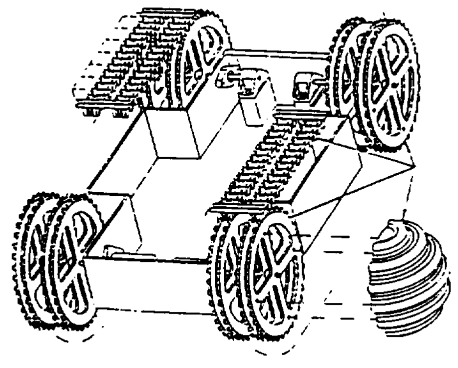


Fig. 7 Tank-track-style autonomous lunar rover (without control system and sections of track cut away)

### Structural frame and body

The body of the rover acts as an external frame and all of the components are mounted directly onto it. The body is made of composite plates. The composite structural plates consist of a foam core sandwiched between two thin aluminum sheets. The aluminum sheets are bonded to the foam core with epoxy resin. The foam core that we have specified is Divinycell HT 110 with a density of 7.0 $lb/ft^3$. 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 internal parts 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

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 were initially traveling forward and somehow became inverted, the motors would reverse direction, and the rover would continue going forward.

The second feature allows the rover to avoid obstacles. The system senses when the rover encounters 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 would 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.

### Drive Train and Tracks

The rover is driven by an external track system consisting of two separate tracks. The two tracks run independently 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 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 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 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. 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 and require 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, and 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.

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, 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 align them 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.

## 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 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.

### 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 rather than a 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 one-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 were 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, the reliability of the components would increase.

## Summation

Using the Quality Function Deployment method of design, the senior design class from each semester developed a small micro-rover based on separate customer requirements. The first semester's project for the MESUR mission provided a simple, lightweight, and reliable machine that accomplished the customer requirement of obtaining a rock sample from the Martian surface. It can also obtain multiple samples at each site. This feature adds a great value to the MESUR mission with minimal costs. The second semester's Autonomous Lunar Rover is capable of reliably transporting a sensor across the surface of the moon to gather important information. The development of prototypes of these designs showed the successful achievement of these goals.

## References

1. Ames Research Center, MESUR Mars Environmental SURvey. Ames Research Center, Moffet Field, California: July 1991.

2. Leidic, C., Ames Research Center Phone Conference, October 1991.

3. Bekker, M. G. Introduction to Terrain-Vehicle Systems, University of Michigan Press, 1969.

4. Bekker, M. G. Theory of Land Locomotion; The Mechanics of Vehicle Mobility, University of Michigan Press, 1956.

5. Comer, David J. Digital Logic and State Machine Design, 2nd Ed., Saunders College Publishing, 1990.

6. Cooper, Henry Jr. Apollo on the Moon, Dial: New York, 1969.

7. Goetzel, Claus G., Rittenhouse, John B. Space Materials Handbook, Lockheed Missle and Space Company, Addison-Wesley, 1965.

8. Johnson, Curtis D. Process Control Instrumentation Technology, 3rd Ed., John Wiley and Sons, 1988.

9. Kopal, Zdenek. Physics and Astronomy of the Moon, 2nd Ed., Academic Press: New York and London, 1971.

10. Lynn, Douglas, "EE 344: Digital Circuit Lab," University of Idaho, 1991.

11. Moon, The. Encyclopedia Americana: , International Edition, Vol. 19, Grollier Inc., Danbury, CT, 1991.