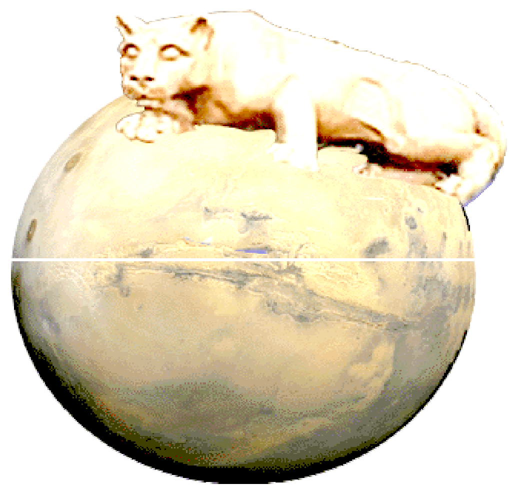
SCALING THE MARTIAN WALLS OF TIME



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1. SUMMARY

On Earth, when scientists want to investigate planetary history they take a core sample, with deeper fragments corresponding to older materials. In essence, descending through sedimentary layers is like going back in time. But creating a robot capable of taking samples more than a few meters below the planetary surface is still beyond the current available technology. The **cliffhanger** idea takes advantage of the natural surface features of Mars to explore the history of the planet without digging. So interesting and difficult questions can be answered not with the brute force of a drill, but with creative mission design.

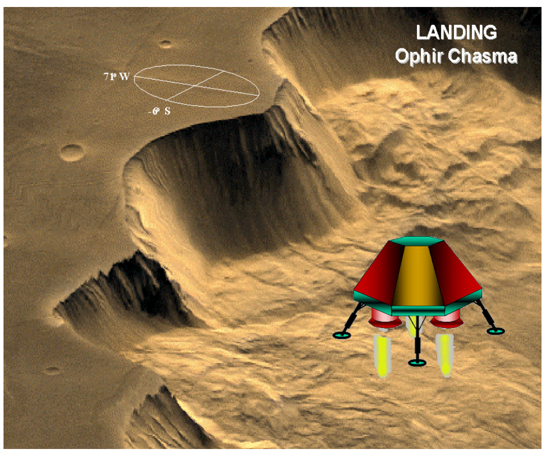

Figure 1. Landing near the cliff in Ophir Chasm.

Penn State University HEDS-UP team has designed a novel Mars mission approach. A main Lander with a Rover and a Cliffhanger (Figure 2) will land near cliffs of Valles Mariners (Figure 1). Especially design canon (gas, guided munitions or rocket) will deploy a long rope into the canyon. The rover will carry the cliffhanger to the edge of Valles Marineris following the rope, attach the cliffhanger to the rope. The Cliffhanger will then climb a 2 km down the rope and will allow the team to study sedimentary layers of rock on the side of the cliff. Samples and high-resolution images will be taken and delivered to the Lander for further investigation (***optical multispectral imaging microscope***, ***spectrometry***) and sending the results to Earth.

The robot has been designed to have the capability for locomotion at any angle (including somewhat uphill slopes) but maximum effective motion will be achieved at descent angles from 70-85 degrees.

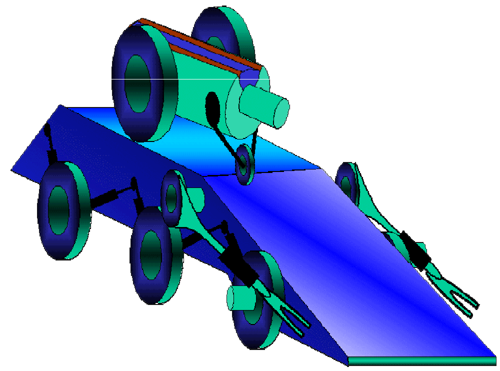

Figure 2. Rover and Cliffhanger.

After the mission of rope-climbing is completed, the Rover am Lander will embark on another long-term mission to provide meteorological and geological data over a long period of time (***long-term Mars Observatory***), and perform acoustic and seismic experiments on the surface of Mars in preparation for human arrival.

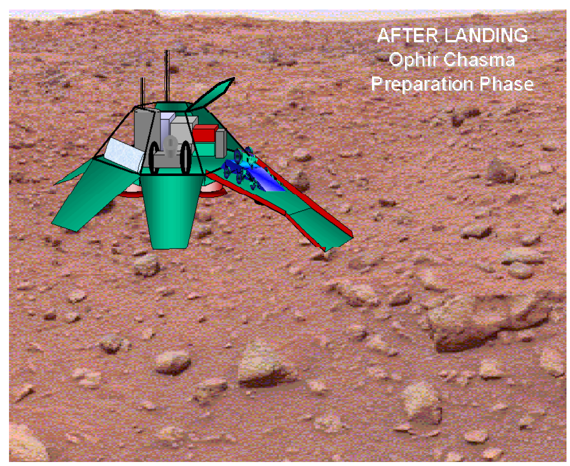

Figure 3. Lander and Rover

2. INTRODUCTION

As scientific observations of Mars create a greater understanding of the planet, and appease basic inquisitions, the unanswered questions remaining continue to become more difficult to investigate. These more elusive answers will require future missions to escape from the constraints imposed by the successes and failures of missions past and embrace more unconventional yet thought-out ideas. Until exploration evolves from sending landers and rovers designed for disposable data collection, to attacking more adventurous robotic goals and beginning manned exploration of the planet, many scientific problems will remain unsolved.

This mission design will serve as an excellent first step in this evolutionary process. By using three specialized modules—a lander, a rover and a cliffhanger—it will be possible to take advantage of the natural features of the Martian surface to enhance understanding of the geologic and biologic history of the planet as well as pave the way for future manned missions.

Primary Science Objective:

The primary objective of the mission is to investigate of sedimentary layers of the walls of the Valles Marineris canyon system. The cliffhanger module will utilize a climbing rope launched by and attached to the lander to descend along the side of the cliff, taking samples and measurements at regular intervals. The rover will then return the samples to the lander for more exhaustive experimentation. This system will not only allow scientists and engineers to thoroughly examine Martian surface and subsurface materials, but will also answer questions about the origin and geology of Mars as well as the history and future of the solar system. And, while the large doses of solar and cosmic radiation on the planetary surface may make detection of life there problematic, deeper sedimentary layers will shed some light on the issue of the possible evolution of life on the planet.

Secondary Science Objective:

The secondary objective of the mission involves the maintenance of a long-term observatory on the Martian surface. Past undertakings, including the Viking and Pathfinder missions, centered on modules whose usefulness ended after a few months. For this mission, the lander and rover modules have been specifically designed to survive the harsh conditions of the planet for years while continuing to take scientifically useful measurements indefinitely. No mission yet has provided the long-term characterization of the Martian environment that will be a crucial element in the design of manned missions.

3. OUR APPROACH

Students enrolled in the cross-referenced EE/ME 497 class at the Pennsylvania State University completed the work reported. Participating students had little to no prior knowledge on the subjects of Mars exploration or robotics. Thus, in order to attain the proper background knowledge of the subject, the students began work on general science tasks.

3.1 Science of Mars

Science tasks, including the search for life, the climate of the planet, and geology and planetary structure, focused on specific areas of interest in the study of Mars.

These science tasks accomplished two main objectives. First, by investigating the known scientific facts and theories of Mars, the students were able to understand better what remains unknown about the planet. These gaps in knowledge were key in mission definition decisions.

Secondly, the study of the Martian environment provides a deeper understanding of the obstacles facing manned or robotic missions to the planet. For example, the simple fact that Mars lacks a strong magnetic field makes the use of any kind of compass on the planetary surface impossible. Also, an understanding of the composition and properties of the soil of the planet is crucial to the design of solar arrays that will overcome the problem of dust deposition that will ultimately plague any mission requiring solar power for an extended period.

After the completion (reports [1] to [13], see references) and presentation of the general science tasks, students moved on to a series of robotics design tasks.

3.2 Robotics State of the Art

These projects (reports [14] to [22], see references) focused on specific aspects of robotics design such as locomotion, control, sensing and actuation, with an eye towards adapting recent advances in these areas for use on the Martian surface. The team was thus able to gain a basic understanding of the current state of robotics design. They also studied the past successful and not so successful robotic mission to Mars.

Once the students had acquired the requisite background knowledge it became necessary to choose specific mission objectives to focus design efforts.

3.3. Important Possible Future Mars Missions

At first, the team participated in a simple brainstorming session that produced more than 25 possible mission objectives for consideration. Since caves would provide an ideal shelter for the first manned missions to the planet one such idea included a search for subterranean caves and lava tubes with a ground penetrating radar device. Other ideas focused on in-situ resource production of propellants or volatile metals such as lithium, which could be burned as an efficient fuel source.

3.3 Mission Selection Criteria

In the final analysis, the criteria that were used to choose the mission objectives were pared down to a few, based on how well the mission will support the following:

- Attempting an innovative mission never proposed before.
- Uncovering the history of geology and biology on Mars
- Public involvement and interest
- Preparation for future human missions to Mars
- Enhancing scientific knowledge and advocate technologic advances in general (outside of the Martian environment).

First, in conjunction with the work done on the general science tasks, the team wanted to choose a mission that would sate scientific curiosity by investigating questions that have up to this point been unapproachable.

Questions about the geologic and biologic history of Mars have heretofore been very difficult to answer because of the lack of diversity in the depths of sample measurements. Past missions took measurements and samples at a variety of locations on the planet—but all the data collected were from the Martian surface.

On Earth, when scientists want to investigate planetary history they take a core sample with deeper fragments corresponding to older materials. In essence, descending through sedimentary layers is like going back in time.

But creating a robot capable of taking samples more than a few meters below the planetary surface is still beyond the current available technology. The cliffhanger idea takes advantage of the natural surface features of Mars to explore the history of the planet without need of digging. So interesting and difficult questions can be answered not with the brute force of a drill, but with creative mission design.

The next criterion used to decide between possible mission objectives focused on the need for public involvement and interest. When the Mars Pathfinder mission touched down on July 4, 1997, for example, the associated web sites received an average of about 50 million hits a day during the first three days. The team wanted to choose a mission that would rekindle and sustain this kind of excitement—and the cliffhanger mission seemed the perfect vehicle for this.

The mission also needed to be part of an evolution towards a more extensive investigation of Mars. It is imperative to increase preparation for future missions—manned and unmanned. For this reason, the team decided upon the ***secondary mission objective of a long-term observatory.***

Planning for future missions will depend upon precise characterization of the Martian environment. Unfortunately, past attempts to provide this characterization have failed in their limited duration.

The long-term observatory will focus on furthering theories of Martian geology and climate, which are currently based on a limited amount of surface data. Characterizing the atmospheric turbulence at the surface of the planet and better understanding the size and nature of the dust particles present in the air will help evaluate current climate models which focus on the importance of dust in seasonal changes. These investigations could also lead to more accurate prediction and categorization of damaging Martian dust storms, which could potentially endanger a manned mission.

The final criterion the team considered centered upon the prospective missions' ability to enhance scientific knowledge and advocate technologic advances outside of the Martian environment. This interdisciplinary cooperation is an area often overlooked in mission planning which is assuming greater importance in these times of strict budgetary constraints.

The team believed that the primary cliffhanger mission would serve as an excellent catalyst to future development in a potentially exciting area of robotics design. Robots similar to the one used on Mars could be employed, for example, in the investigation of volcanoes and possible landslide and avalanche hazards. Since the robot will handle well in difficult terrain, it might be of interest to the military to obtain a tactical advantage in mountainous and urban areas. It will also serve as a relatively low-cost pioneer to chasms, valleys, craters and volcanoes on Mars and other planetary environments before more sophisticated and specialized robotics can be created and utilized in space.

Several of the experiments placed on the lander will also provide useful insight into earthbound phenomena. The climate studies, for instance, will give meteorologists a look at the physics of weather and climate on a world that, in many ways, is different from our own. By comparing these variances, it will be possible to achieve a deeper understanding of how weather works here on earth.

Once the team settled upon the primary and secondary mission objectives, students returned to their design tasks with very specific goals in mind. Students were separated into three groups—lander, rover and cliffhanger—with representatives from the different design tasks divided evenly amongst the three new groups. In this way, the team was able to provide expertise in all areas.

3.4 Robotic Experiments

Because of relatively small financial support for the project, we were not able to build any advanced system or subsystem of the robot. Most of the work in the prototyping focused on building some simple model of the robot using wood, plastic, and paper and other creative materials. The importance of modeling, for the HEDS-UP team, was to determine usability, tolerances, and to visualize the developed concepts and ideas. Examples that demonstrated robotic scenarios of the mission are shown in Figure 4A and Figure 4B.

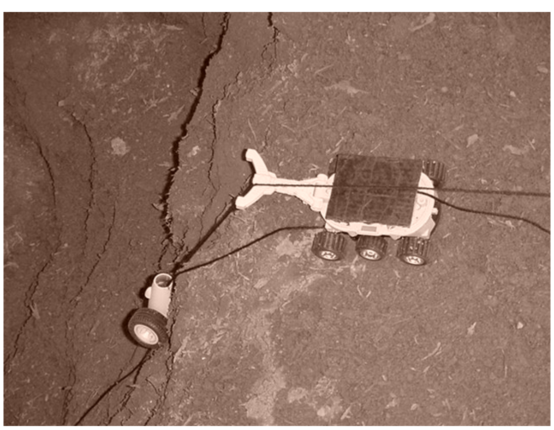

Figure 4B. Mockup of Rover and Cliffhanger on the cliff.

Also, some robotic experiments were performed using LEGO robotics. This includes experiments like command the robot to drive a certain distance, stop for a given amount of time, go in reverse, and spin, and building and controlling catapult that launched a ball. Another robot was also built that drove on two motors and had a rotating arm that was activated by the third motor.

A different team of students took a training lesson on how to use the tools available at the Penn State Learning Factory and how to use a rapid prototyping machine that layers paper upon paper to the design specifications. Each student from Modeling Team attained an access to the facility after completing a four-hour safety course. This safety course allows the certified student access to power tools and some machining equipment.

Figure 4B. Robotics Experiments

4. INVESTIGATION RESULTS

4.1 The Primary Mission

The primary mission is to explore and collect data and samples from the canyon walls of the Valles Marineris, and to do this all three robotic modules must work together. From the engineering system design point of view, all three units should be built using ***modular approach*** for easy modification, low cost and affordable upgrades. The digital electronics should be ***reprogrammable*** to enable software upgrades and remote corrections to potential problems during the mission. All three units should communicate with each other using modern ***spread-spectrum (low-power) digital communication*** technology with easy access by everyone to anyone resources during the mission.

The Lander

In order for this mission to be a success the lander must touch down within 1000 to 2000 m of the edge of the cliff. This will be accomplished by using jet propulsion to control the landing. We are assuming that by the time the proposed ***robotic rope-climbing mission*** can be designed, the precision of landing on Mars will improve significantly compared with today's technology (Figure 1).

The Lander module will serve as the power source and communications base for the mission. It will be constantly connected via a wire cable to the cliffhanger and rover during the primary mission.

Rope Launch

The first step of the primary mission will be to launch a rope over the edge of the canyon. The rope must be deployed in a fashion that will allow at least two kilometers of rope to hang over the side of the cliff. This requires a ballistic, parabolic, path. Obtaining the correct path requires an equation that includes gravity, initial velocity, mass of object, angle or launch, and the distance to the cliff. The gravity of Mars is known, the mass of object is the end piece plus the integrated weight of the rope as it is pulled out, and the initial velocity and angle of launch will be derived from the equation when it is solved. The only part of the equation that will not be known is the distance to the cliff.

There are two ways to acquire the distance to the cliff. The first and most expensive would be to include a targeting and tracking system with the Lander, much like a military weapons system would have. An alternative would be to use a satellite photo with the Lander and cliff in the same image. The difficulty with the second choice is the current imaging systems, on satellites orbiting Mars, do not have a resolution high enough to image the Lander. Once the distance to the cliff is obtained the ballistic equation can be solved for the initial velocity and angle of launch.

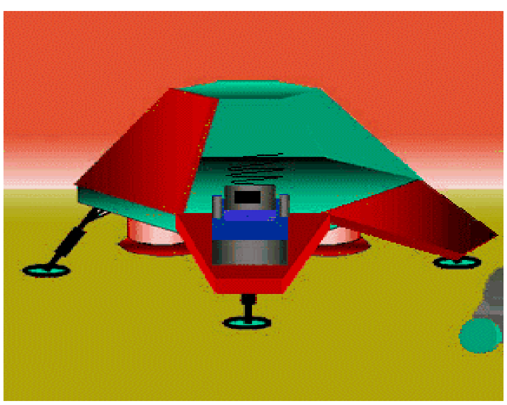

Figure 5. Firing the rope.

The firing system will include a rope drum, containing 2-3km of 4mm rope wrapped around a center cylinder, for an almost frictionless release. Another 4-5km of rope will be wound around a flywheel wench. The center of the rope drum will contain the firing mechanism.

There are two ways to launch the rope. The first is to use a rocket with the rope attached. The rocket would be able to have programmable flight characteristics. Foreseeable difficulties with using a rocket are: using explosive fuels to propel the rocket and the flight will only be a few kilometers and the air pressure is 1/100th of Earth's which could lead to flight control problems. The second way to launch the rope is to use pressurized gas. The gas would be kept in a tank and then released into a compression chamber to be pressurized for launching. Possible difficulties using pressurized gas are being able generate enough pressure to launch the weight and rope several kilometers, and the large force applied on the lander during the launch.

In order for the cliffhanger to be able to efficiently climb up and down the cliff using the rope the rope should be anchored to the cliff and to the lander. To anchor the weighted end we have thought to use a spike firing system, much like the piton guns used by mountain climbers. The pitons would initially be inside the weighted end, attached to a pressure pins. Once the weighted end touched down on the cliff face the pressure pin would be triggered, releasing the piton securing the launched end of the rope to the cliff.

Table 1. Rope Specifications for Different Ropes

Diameter	4mm	3mm	2mm
Length	7km	7km	7km
Mass	10kg	6kg	4kg
Breaking Strength	3.2kN	1.8kN	0.85kN

After the Lander fires the rope it deploys the rover with the cliffhanger to begin stage two of the primary mission.

The Rover

The Rover's primary mission is to deploy itself from the Lander via ramp system and transport the Cliffhanger to the edge of Valles Marineris (see Figure 2). The rover and cliffhanger will always be attached to the lander via a rope with a communication / power cable inside. This cable will be carried on the rover in a spool and be laid down as it travels. This connection will ensure that the rover and cliffhanger have enough power to complete the mission. Additionally, long distance wireless communication requires a significant amount of power and is unreliable. A direct connection to the lander would eliminate these problems. Estimations for the mass of 4km of this cable are on the order of 6 to 10 kg, which is a reasonable size for the 50 kg rover.

Rover Navigation

Multiple methods of navigation will guide the Rover to the edge of the canyon. The rope launched by the Lander will ***have encoded marks*** along the rope for rover and cliffhanger to know its actual position on the line. Also the rope will have a ***transponder*** encased inside of the end weight. A transponder is activated for transmission by reception of a predetermined signal sent by the Rover. Periodically, the Rover will use this navigation method to determine the distance and direction it should travel. In conjunction with the transponder signals, a ***laser obstacle detection*** system is used to prevent collisions, enabling the Rover to navigate around rocks, cracks, and other obstacles. In addition, a ***camera*** will capture images to send back to the Lander and Earth. These images will update NASA scientists on the progress of the Rover's travels, as well as aid in navigation. This camera will also be used to locate the rope at the cliff edge. An ***odometer*** will use wheel rotations to calculate the approximate distance traveled. This information will also be used to control the winch that will unroll the Lander-Rover power line.

Future navigation methods on Mars may (and probably will) include the ***Global Position Satellite System.***

Using the camera images and human control, the rope will be located and made accessible to the Rover's mechanical arm. While the arm rotates from the front position to the rear position, the Rover will drive under the path of the rope, thus laying the rope directly over the Cliffhanger. As the arm rotates to the rear position, the axle clamps that previously locked the Cliffhanger in place are released. The Rover's camera and the Cliffhanger clamp sensors will assure that the rope is in place. Next, the Cliffhanger is activated and the drive wheels will roll it off the front ramp of the Rover. Once the Cliffhanger is at least one meter away from the Rover, the mechanical arm will rotate back to the front position and serve as a pivot point for the rope. The Rover-Cliffhanger power line winch motor will release a length of power line equal to the distance traveled by the Cliffhanger. Rotation in the drive wheels (before reaching the canyon edge) and rope tick mark counters or number shimmies (during the descent) will calculate the length of power line to release. As the Cliffhanger shimmies down the rope, the correct amount of power line is released from the winch.

The Cliffhanger

The Cliffhanger robot is an innovative style of robot that is designed to work in the vertical world. While past missions to Mars in the past have been very successful in exploring the surface of Mars, they were unable to go below the surface, where the history of the planet lies. Although it would be neither practical nor monetarily feasible to drill two kilometers into the surface of Mars to collect data, we are still left with another option. Just as scientists have been able to study the history of this planet by analyzing the walls of the Grand Canyon, the Valles Marineres on Mars opens up a window that allows scientists to peer into its history. Once on Mars, the Lander (which we are assuming will land within one or two kilometers of the cliff edge) will deploy a rope over the edge of the cliff. For this mission we are using climbing rope, made of nylon that is four millimeters in diameter. Climbing rope is ideal because of its extreme strength (such climbing rope can bear a force of more than 3 kN), durability, ability to withstand large amounts of friction, and light weight (approximately 9.8 g/m). Once this rope has been deployed, the Cliffhanger will "ride piggyback" on top of the Rover to the cliff. At this point the Rover will place the rope into the clamps of the Cliffhanger, where it will proceed to climb down the rope approximately two kilometers, collecting data at certain points.

Cliffhanger design

The Cliffhanger's design provides a maximum amount of protection and mobility, while at the same time ensuring that all of the experiments are easily accessible. The primary section of the Cliffhanger is an octagonal prism shaped chamber (see Figure 6), which houses the experiments. Each face of this chamber is 10 cm wide, with a length of 30 cm. This inner component is encased in an outer cylinder, which has a large opening facing the cliff face, allowing the equipment to have access to the wall. The cylinder will be 31 cm in diameter and 37 cm in length. This outer shell will have a window that will expose the cliff face measuring 20 cm in length, and 12 cm across. Two clamps stick out from the ends constituting the Cliffhanger's system of grasping the rope. A key feature of the entire system is that it is 'C' shaped, in that it has a wedge cut out of it. Since the Cliffhanger does not start off attached to the rope, it must have a system for taking in the rope. As mentioned before, the Rover feeds the rope into the Cliffhanger. This is done by laying the rope into the opening of the Cliffhanger. Measures are taken to prevent the rope from falling out of the clamps (this will be discussed later).

Climbing Mechanism

The movement of the Cliffhanger up and down the rope is very difficult considering that it is hanging a large distance above the valley floor. As discussed earlier, there are two clamps located on the ends of the outer cylinder (the design of the clamps will be discussed later). The top clamp will be encased in a cylinder 10 cm long, and 6 cm in diameter. The bottom clamp consists of two components: a clamp and a pump. When compressed, this telescoping component is 20 cm in length, and 7cm in diameter. The ten centimeters nearest the body are dedicated for a hydraulic pump. The second ten centimeters will be the telescoping section containing the second clamp. The second clamp will slide in and out of the shell as it is either pushed or pulled by the pump. These three components allow for the climbing of the Cliffhanger robot. As the Cliffhanger descends, the top clamp will hold onto the rope when the robot is in the compressed position. The bottom clamp will release, suspending the weight of the entire robot by the top clamp. The pump will push the bottom clamp down, and the Cliffhanger will then be in its expanded position. Once in the expanded position, the bottom clamp will grasp the rope, and the top clamp will release the rope. Although the top clamp will not have a firm grip on the rope, it will not allow the robot to fall off of the rope. The pump will lower the main body down, and the Cliffhanger will return to its compressed position. When the Cliffhanger is ascending the rope, the process simply reverses itself as the pump hoists the robot up the rope.

The process outlined above works well assuming that the cliff face remains a sheer face for the entire two kilometers that the Cliffhanger will descend. However, should the cliff face jut out at any point, the Cliffhanger will need to overcome this obstacle. For this reason there will be a total of six wheels on the robot. There will be two main drive wheels, forty centimeters in diameter each located in the center. Four smaller, neutral wheels will be placed on the outer corners forming a base. These smaller wheels will not only provide a good base, but they will also help to guide the robot while it is driving. This system allows the Cliffhanger to be adaptable to both the vertical and the horizontal worlds.

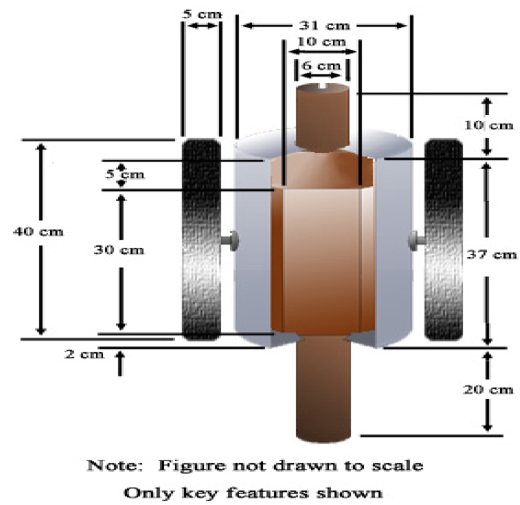

Figure 6. Cliffhanger diagram

Certainly the most crucial aspect of the Cliffhanger is the clamp. The clamps are completely responsible for ensuring the safety of the Cliffhanger. For this reason the clamps must be designed in a manner that will allow for minimal errors. The method that works best is one that requires only two quick surges of power; one to lock the clamp, and one to unlock it. The main challenge with a system is that it requires a constant stream of power to hold the clamp in either a locked or an unlocked position. The continuous, uninterrupted stream of power is required. This will not only cause increased power consumption, but will hold a greater chance for error. A loss of power, if even for only a mere fraction of a second, could result in the robot slipping off of the rope. The design of the clamps is actually a very simplistic one. They are cylinders with an opening for the rope to enter (see figure below for clamp design). The rope falls down the funnel-like opening into a semi-circle cradle, which is reinforced against the outer wall of the clamp so as to stabilize it in place. Across from the cradle is the face of the clamp.

Approximately seven millimeters across and three to four centimeters long, they consist of a flat metal face with tiny metal jags that stick into the rope and prevent slipping. A sliding door covers the remaining opening, preventing the rope from escaping the grasp of the clamp.

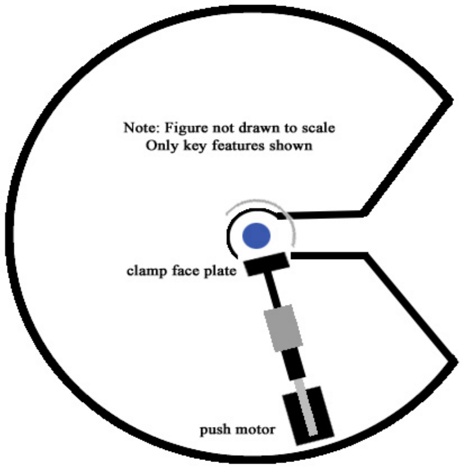

Figure 7. Cliffhanger rope catching mechanism.

The jagged metal plate that serves to grasp the rope must be pushed into and pulled away from the rope during the clamping process. For simplicity, the clamping face has only two positions to lock into, clamped (pressing the rope) and unclamped (releasing the rope). The locking process will model that used to retract the ink well on certain ball point pens. From the unclamped position, a force pushing the clamping face in will lock it in the clamped position when released. When pressure is reapplied in the exact same manner, the clamping face returns to the unclamped position when the force is removed.

There are two different types of mechanisms that perform such an action. The first type involves a geared turn cylinder with slots moving along a cylindrical grooved track, being pushed by a teethed cylinder. When it is pushed initially below the level of the grooves and released a spring forces it upward, causing the geared turn cylinder to turn with respect to the push-button and the outer track. Once the push button is pressed again, the spring causes the turn cylinder to turn once more, realigning its slots with the grooves on the track, allowing it to retract. A much simpler version of this locking system involves steel bearing on a heart shaped track. When the push button is pressed, the steal bearing is moved clockwise along that track into one of the two bulbous regions at the top of the heart shape. When the push button is released, a spring forces the ball into a recessed position in one of the two drop points of the heart. These points represent the clamped and unclamped positions, depending on the orientation of the heart shaped track. Either of these two methods allows the clamping process to be performed using minimal power, requiring only a push motor to quickly activate the clamping mechanism. Not only is this system more efficient, it is also safer, as the mechanical devices lock the clamp into place, preventing any slipping due to a power surge.

Once the rope has been placed in the opening of the Cliffhanger by the Rover, this opening must, for obvious reasons, be closed off. The solution to this is a rather simple one. Angled tracks will be placed on the cup, which holds the rope. In these tracks will be a curved piece of metal (represented by the gray bars in the figures above and below). When the Cliffhanger is on its “back”, with the opening facing upward, the metal curves will fall back, leaving the full opening exposed. Once the robot is in a more upright position, gravity will pull the metal piece across the opening, thus blocking it. Placing these at certain intervals along the Cliffhanger will prevent the possibility of it losing the rope.

As outlined earlier, there are two separate shells. The outer shell has only one window that exposes the cliff face. The octagonal inner shell contains several experiments. For this reason the inner shell must be able to rotate with respect to the outer shell, allowing the different experiments to face the window. Also, there is the possibility that the entire Cliffhanger could twist away from the cliff face while climbing. Due to this possibility the outer shell must be able to rotate with respect to the clamps.

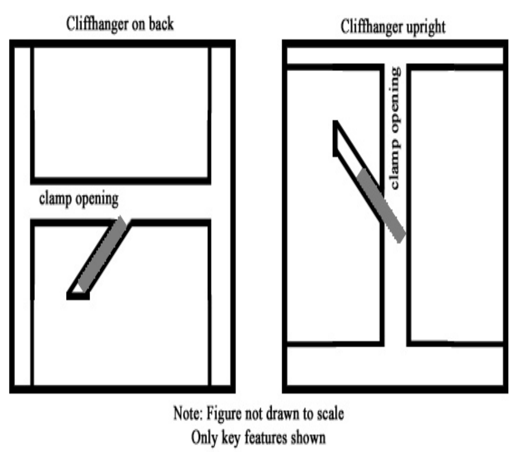

Figure 8. Cliffhanger rope trap mechanisms.

As shown in the figure 9, both shells were designed to be independent of each other, and have the ability to rotate with respect to the clamps. 'C' shaped bearing tracks are then placed in three locations, between the clamps and the outer shell, between the clamps and the inner shell, and between the inner and outer shells.

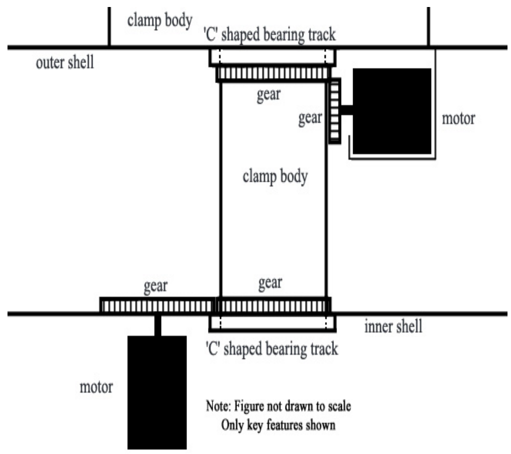

Figure 9 Cliffhanger gear mechanism.

Also, there are two different motors controlling separate gears. These gears will rotate the inner and outer shells with respect to the top clamp. Since the top clamp will remain stationary with respect to the rope, the inner and outer shells will turn with respect to the rope. These gears are illustrated in the figure 9.

Cliffhanger instruments

The Cliffhanger will only be involved in the primary mission. It has numerous experiments to perform as it scales down the canyon wall. A high-resolution, wide-angle camera will be built into one of the Cliffhanger's faces. This will be able to take detailed close-up pictures of the walls of Valles. The clamps will be able to move the Cliffhanger the same distance as the wide-angle lens' focus. The camera will release the shutter once every time the cliffhanger moves. This will enable us to compile a complete work-up of the wall.

Soil Samples and Ultrasonic Drill

An ultrasonic drill will be built into another side of the Cliffhanger. This drill will be able to bore a half-inch hole in the rock or soil on the wall. The hollow drill will also extract the sample. A vacuum chamber will suck the sample back into a small tube, where a filter will stop the sample (see Figure 10). Once the sample has been collected, the revolver will rotate, exposing a new tube. This method will enable the Cliffhanger to collect numerous samples which will be taken back to the Lander for analysis. The ultrasonic drill has only a minimal kickback, therefore precautions for anchoring the Cliffhanger to the cliff face before drilling are not necessary.

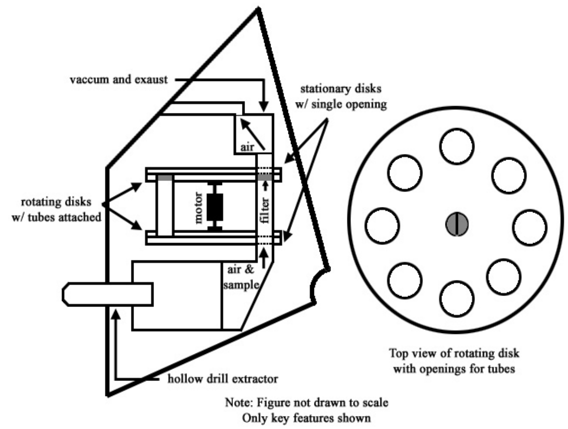

Figure 10. Cliffhanger ultrasonic drill and sample collector.

A third geological instrument may also be included. The Alpha Proton X-Ray Spectrometer, or APX. This instrument is able to determine the chemical make up of the surface. Every time the cliffhanger moves, the APX will look at the wall. A composite of the data gathered during the Cliffhanger's mission could help us to better understand the geological history of Mars.

Miscellaneous environmental experiments will also be built into the cliffhanger. These include pressure, temperature, and wind sensors. This will enable us to learn about the climatic conditions inside the canyon. It is possible that the canyon would be the most likely place to start a human settlement. The atmospheric pressure could be great enough at the bottom to grow plants. The environmental instruments will help us figure that out.

4.2 The Secondary Mission

The secondary mission is to have a repertoire of experiments that will be long lasting and continue to provide valuable Martian data over an extended period of time.

After the Mars Cliffhanger robotic team has performed their primary mission, the Lander will begin its secondary mission as a long-term observatory. We would like this secondary mission to last in excess of a decade. The goal of this mission would be to provide extensive information about the Marian climate and weather patterns, to give insight into the frequent dust storms and how to best prepare for them, and to act as a set of eyes and ears on the Marian surface. Throughout the secondary mission, the Lander will continue to provide power for the Rover's secondary mission. The detailed analysis of data provided by the Lander's secondary mission, would allow future Mars missions to be well prepared for the hostile Martian environment.

The lander will also attempt to improve our overall model of the Martian climate and internal geologic structure with its measurements. The thin Martian atmosphere, for example, necessarily leads to large temperature gradients. Spatially, the sun's rays rapidly heat the surface of the planet without much direct effect on the temperature of the lower atmosphere. Temporarily, the heat stored in the ground during the day is rapidly dissipated at night. By measuring the differential heating of the planet and the surface wind turbulence over an extended period of time, meteorologists can get a better idea of the exact magnitude of these gradient—improving their understanding of the effects of this thin atmosphere. This improved modeling ability should lead to more accurate forecasts of what has heretofore been deemed the "unpredictable" Martian weather.

Lander Meteorological Instruments

Several meteorological instruments will be included on the Lander:

Temperature:

Two thermometers, separated by at least 0.75 vertical meters with the bottom sensor at about 0.1 meters elevation, will be used to record daily and seasonal temperature gradients. Taking temperature measurements during dust storms will be a useful aid in recording the temperature drop due to the obstruction of sunlight.

Pressure:

Barometers will be used to determine pressure readings—especially useful if it can be used to predict the commencement of dust storms. Also, Doppler radar could be deployed in predicting when and how dust storms accumulate, and how quickly they move across the landscape.

Wind speed:

An anemometer will be used to measure wind velocity and frequency, daily average wind speeds, and the speed during dust storms. Knowing how fast and when winds pick up (if there are similar daily occurrences) will inform future robotic missions when to retract or tilt solar panels to reduce dust accumulation.

The design of these ground-based weather sensors requires the proper mixture of sensitivity and durability. A mechanical anemometer, for example, would need to be impracticably large due to the reduced atmospheric density and would be far too sensitive to the shocks of lift-off and landing. One possible alternative is an active ultrasonic anemometer, which contains no moving parts but requires significant power (>30 [W]) and is somewhat expensive. The design that seems to offer the best durability with the lowest cost and power requirements is an anemometer which uses the small pressure changes around a vertically-orientated cylinder to estimate wind speed and direction. This design; [38] uses existing static flow sensor technology that could be adapted to the Martian environment with the inclusion of a larger diaphragm for pressure measurements, for example. With no moving parts and a low overhead requirement, this anemometer design seems the perfect fit for the mission.

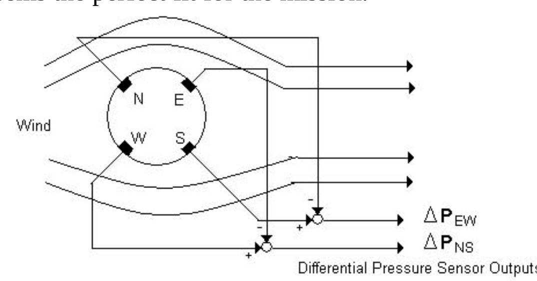

Figure 11. Differential Pressure Anemometer

The corresponding (see [38]) orthogonal components of the wind vector (voltage) are:

$$\mathbf{U_{NS} = sgn(\Delta P_{NS}) * sqrt(2|P_{NS}|/\rho)}$$

$$\mathbf{U_{EW} = sgn(\Delta P_{EW}) * sqrt(2|P_{EW}|/\rho)}$$

Other characteristics of the Martian environment will require the long-term study provided by this secondary mission.

Solar Radiation:

Measuring different aspects of sunlight could make solar power a more efficient source on Mars. Right now, the use of solar energy to power a long-term mission on Mars remains problematic. By knowing precise solar measurements, solar power could be made more viable for necessarily lengthy future missions. By measuring the frequency, amount and the angle of incidence of direct sunlight, it will be possible to better characterize the sun's energy reaching the surface of the planet. Tracking and examining these data over the course of several years could lead to improved solar panel designs.

The direct study of sunlight on the surface of the planet, however, poses a problem—the sun's position varies both seasonally and daily. This variance can be overcome if mechanical mountings are used on the instrumentation required for observation, but these mountings must necessarily contain large numbers of sensitive moving parts. Another solution, which has a wide variety of possible applications, is to employ arrays of fiber-optic cables and optical switching networks. The cables are low cost and lightweight—so they can be oriented in any required direction. For the example of direct sunlight study, tracking the sun's position and choosing the correct input to spectroscopes or photometers can be as simple as determining which cable contains the highest light intensity.

Soil and deposit Layers Sample Analysis:

The samples returned from the canyon wall can also be tested with a minimum of sensitive moving parts using this technology. It may be possible to take measurements of several samples with the same instrument without moving the samples using this idea. Companies such as Ocean Optics have already proved the viability of miniature spectrometers using fiber optics. Advances in the still young field of optical switching methods will continue to improve the capability of this new technology for exploration.

Another important instrument integrated with the above optical technology will be an ***optical multispectral imaging microscope***. The microscopic optical images of samples will be recorded and transmitted to Earth for more detailed analysis.

Dust:

Dust deposition also can lead to decreased solar panel efficiency over the course of a lengthy surface stay. By learning more about the Martian dust, future missions will also be better prepared to handle dust storms. Instruments will measure dust composition, electrical charge of dust particles, and dust deposition rate. This will gain insight into how these tiny particles affect the sensitive instruments of robots sent to survey Mars. Further study of the electrical properties of the dust can lead to the development of more effective electrostatic methods for removal.

But it is not merely the effect of dust upon solar panels that makes the characterization of dust particles scientifically interesting. Current Martian climate models emphasize the importance of dust in the planet's seasonal changes. The type and size of these dust particles, however, has yet to be investigated fully. A combination of lasers and optical sensors can take measurements of the number and size of the dust specks. Measuring backscattering, for example, can provide a mean particle size. This instrument would operate in much the same way as environmental protection sensors currently placed on industrial smokestacks.

Cosmic Radiation:

The Earth's atmosphere acts as a shield against many types of radiation that would be harmful to life and instrumentation. The less dense Martian atmosphere does not filter out many of these harmful rays. Robots and their components that work well on Earth are not protected on Mars from UV and cosmic rays. Instruments will be used to measure UV and cosmic ray indices, as well as the effects on components due to solar storms. Small samples of materials under consideration for use in future missions will be brought from Earth and will be exposed to the elements. These materials can include metals, silicon, circuit components, and solar panel material—anything of interest that may be used on future missions. At appropriate intervals, these materials will be examined by the microscopes and spectrometers within the Lander for corrosion, durability, permeability to dust and cosmic radiation, and robustness. By examining these materials over a long-term mission, the materials best suited for future missions can be used. A similar experiment may be conducted with a small quilt of different types of solar panels. They too can be examined to see which materials hold up best to the Martian environment, dust repulsion, as well as the best power generation and efficiency.

Sound and Infra-sound:

The rover will also play a large part in this secondary mission by deploying a large infrasound microphone—a microbarograph. The microphone requires noise-reduction hoses extending ~100 [m] in multiple directions that will be arranged by the rover. This instrument will collect data from the detonation of small charges placed a safe distance from the lander. The data recorded will give a better understanding of the subsurface composition of the planet. It will provide the detection method of micrometeorites collision with the Martian surface, their intensity and statistical data. This may be a very important factor for designing future human habitats on Mars. But these data will not only be of use in increasing our understanding of Mars. Measurements in another environment much different from our own will challenge the current understanding of the mechanics of wave propagation. These propagation theories are used today in many areas from seismology to troop detection to counter proliferation efforts.

Mars Internet:

The Lander will also contain a multimedia center. This will include CCD cameras for both telescopic and panoramic views. Microphones will provide an audio component to record Martian sounds—the large infrasound array will also serve to help calibrate these microphones. Live video and audio feeds can be relayed back to Earth and will be made available for the general public. The purpose of this equipment serves three functions. First, the Lander can serve as a **"pair of eyes"** to monitor and control the Rover during its primary and secondary missions. It will aid in navigation along the Martian terrain and will help guide the Rover to the correct position in dropping off samples collected by the Cliffhanger. Second, it will nicely complement the meteorological instruments aboard the Lander in monitoring the environment and landscape. Seeing the dust storms in action will enhance the non-visual data collected. Finally, but still importantly, the cameras and microphones will serve to spark interest and maintain confidence in the public. As important as scientific data and discoveries found on Mars may be to all of humanity, the general public does not always see it this way***.*** ***By allowing anyone to go on to the internet and view Martian landscapes, watch a dust storm, see weather maps complete with highs and lows and upcoming dust storms; people will know their tax dollars are going somewhere.*** Even with the space program's high success rate, the recent failed Mars missions have made people wonder why we spend billions on sending a robot to Mars. By setting up cameras on the Lander, and allowing "real-time" access to Mars, we can answer those questions, increase awareness, and increase funding for future missions.

Rover Secondary Mission:

The rover will play a large role in the secondary mission. Using power generated either by its own solar panels or batteries recharged through a docking bay in the lander, it will have its own array of scientific instruments.

Wind, Weather and Acoustic Experiments:

The rover's meteorological and acoustic payload will supplement the data collected by the lander. Mobile wind, temperature and pressure measuring devices will provide a second data point at each sample instant. Perhaps more importantly, however, the rover will carry a small whistle, which it will use in simple acoustics experiments involving the lander. Measurements of sound propagation at specific frequencies over known distances are very useful in determining wind turbulence and temperature differentials. The detailed studies of high frequency sound propagation in the terrestrial environment combined with the measurements taken in these simple experiments will provide a far more accurate characterization of the lower Martian atmosphere than has heretofore been possible.

Seismic Experiment:

Another possible and important function of the rover during long-term observation of Mars would be to help perform some geological seismic experiments. The rover will deploy seismic sensors in predetermined and recorded positions around the landing site. It will then position a detonation charge with the remotely controlled mechanism. The Lander will trigger the detonation, and the travelling waves will be recorded by lander instruments as well as by distributed seismic sensors. Data than can be collected by Rover and transferred to Lander for delivery to Earth's scientists for analysis. The seismic experiment analysis results can provide a valuable information about the structure of the Martian subsurface layers.

Though the long-term observatory has been deemed the "secondary" objective, its objectives are every bit as important to furthering the scientific understanding of Mars and paving the way for further exploration. In fact, even a complete failure of the primary objective would not render the entire mission useless, as would happen with so many other missions.

4.3 Power Requirements

It is estimated that total power required for the mission will be in excess of 1 kW for primary and secondary mission. The danger of frequent dust storms on Mars that can lasts for months and preventing the sun illumination reaching the solar panels, as well as deterioration of solar panels due to dust depositions, will require a backup power system to be present. For this purpose we propose to use a Radioisotope Thermoelectric Generators (RTGs) in the mission - see below.

Power Production

Any electronics package launched from Earth must be equipped with its own power supply. The primary source for power supplies in near earth vicinity is the sun. In order to harness the sun's energy solar panels must be used. Solar panels are only as efficient as the amount of direct sunlight they receive and the conversion efficiency of the panel material. The amount of power provided by the sun can be derived from the Stefan-Boltzmann law:

$$F= (4\pi R_s^2)\sigma T^4$$

where σ is the Stefan-Boltzmann constant equal to $5.67*10^{26}$ $Wm^{-2}K^{-4}$ and R_s is the radius of the sun. Which then leads to intensity I at distance R from sun.

$$I=F/(4\pi R^2)$$

It can be calculated that in near Earth vicinity solar panels will receive $1400Wm^2$, but as can be seen in equation (2) the sun's intensity falls off by an inverse square relationship. This means that as solar panel travels outward from earth and away from the sun it's available power will decrease by at least R^{-2}.

Our planned mission is for a long-term observation post on Mars' surface. According to equation (2) Mars receives $595Wm^{-2}$ of energy from the sun, which is approximately 43% of the intensity that is received at Earth. By using the intensity at Earth and Mars, X being the solar panel size in m^2, one can see that a solar panel would have to be $2.35m^2$ on Mars to produce the same amount of power a $1m^2$ panel would in near Earth vicinity. This means that a solar panel has to be 235% larger on Mars. Once you apply the up to 18% efficiency of a solar panel, you find that it would take a panel of approximately $9.4m^2$ to provide 1kW of power, even during the periods of maximum solar intensity.

$$596Wm^{-2} * X = 1400Wm^{-2}$$

In addition to the lowered available intensity and efficiency of current panels, solar panels can only produce energy when the sun is within line of sight, meaning that batteries must be included to provide power when it is dark. As the distance from the sun increases during winter season on Mars, the second power supply must be used to produce power alternative to the solar panels, especially since our mission is expected to last a decade or more in unknown and unpredictable conditions.

Radioisotope Thermoelectric Generators:

Since as early as 1961 NASA has used Radioisotope Thermoelectric Generators (RTGs) to power satellites. They have been successfully been used on 25 missions, including two to Mars, seven to the Moon, and ten around Earth. Pioneer 10 / 11 and Voyager 1 / 2 contain RTGs that are still operating, after 28 years in one case.

RTGs have no moving parts and produce heat, which is converted to electrical power. The heat is a byproduct Pu^{238} alpha decay. As the plutonium decays alpha particles will be ejected, and the RTG uses the alpha particles to heat a piece a metal. The heated metal is attached to another metal that is kept at a lower temperature, in most cases the ambient of space. A current is induced between the two metals through the Seebeck Effect.

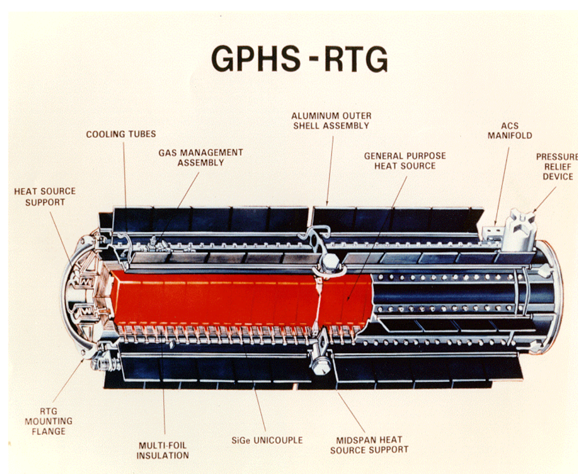

Figure 12. Radioisotope Thermoelectric Generators

RTGs use 11 kilograms of plutonium dioxide, which means that 30% of the total mass of the fuel, 3.3kg, is actually oxygen. The system is divided into 18 modules each of which contain 4 plutonium pellets. The plutonium is refined to a ceramic state that is fracture resistant. Other safety measures included are a graphite foam shell for heat resistance and iridium cladding on each pellet. The cladding is used to keep the plutonium encapsulated after an impact. The safety features designed for RTGs have worked on two occasions already.

Power provided by an RGT is available for 87.7 year, do to the half-life of Pu^{238}, with approximately 96% of the initial power at year 5. The conversion ratio for power from plutonium is 1W from .0027kg of Pu^{238}. Previous missions containing RTGs:

Table 2. Examples of existing RTGs

Satellite	# of RTGs	Weight	Initial Power	Power after X yrs
Ulysses	1	56kg	283W	223W after 9yrs
Cassini	3	168kg	850W	628W after 11yrs

RTGs are a viable energy source for sustained missions at distances from the sun greater than Earth's. They are built with multiple safety features, to insure plutonium containment should a launch or Earth flyby fail. They contain no moving parts, which reduces the possibility of a mechanical failure, such as unfurling a solar panel. RTG efficiency decreases, 4% over 5 years from decay, over time far slower than a solar panel's does from dust accumulation, 1% over 3-4 days. The only negative factor of the RTG is its mass, 56kg, but this can but rectified by replacing other redundant systems.

4.4 Site Selection

Some students of our team were assigned the task of choosing a suitable landing site for the mission. This group searched for landing sites adjacent to the large canyon systems that would best facilitate successful completion of the primary mission objective. The site, therefore, must be relatively clear of large boulders and other obstacles that could interfere with the rover's ability to transport the cliffhanger robot to the canyon edge. This clearing also needed to be large enough to overcome the lack of precision in landing.

Perhaps the most important requirement for the mission, however, is the slope of the canyon. The cliffhanger robot was designed for

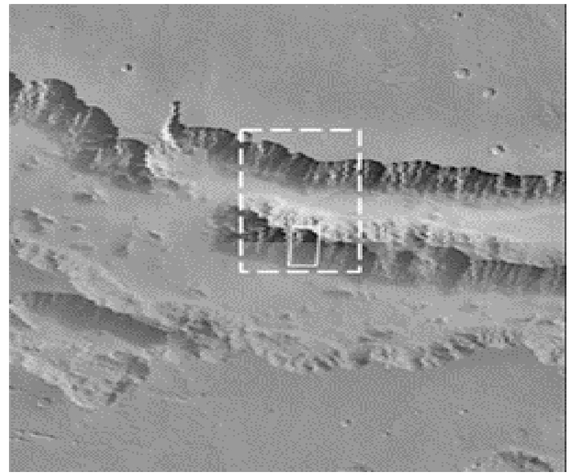

Figure 13. Sedimentary layers in Coprates Chasma

use on steep slopes (it is most effective on slopes ranging from 70-85 degrees) so a site with the sheerest cliffs would greatly facilitate the successful completion of the primary mission objective. The site also needed to be as close to the equator as possible to mitigate the effects of Martian seasons on the power provided by the solar panels.

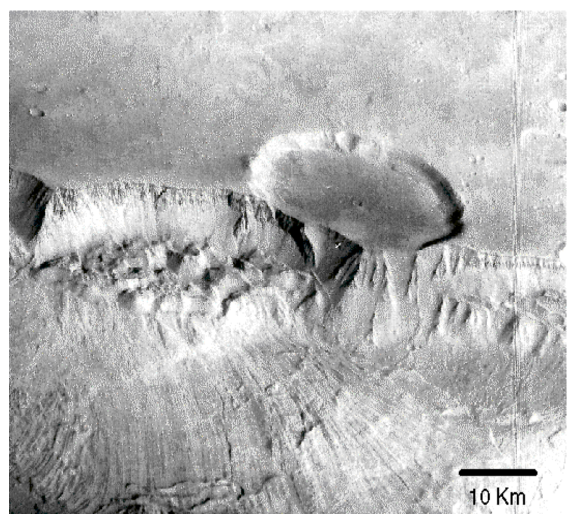

Figure 14. Gangis Chasma

Due to the many constraints and necessities presented by the proposed mission, the team's first selection of the possible landing sites is along the Coprates Chasma. This canyon system is also located in the eastern region of Valles Marineris—along 7° and 17° south and between 69° and 52° west. The site located at Coprates Chasma has a much larger area for landing. The image shown in Figure 13 is a section of the canyon taken by the Mars Orbital Camera, the region width is approximately 100 km. As can be seen, the region surrounding the cliff edges is relatively smooth and the canyon walls are greatly sloped, allowing a good descent path for the Cliffhanger. The area around Coprates Chasma is void of excessive impact crater regions, allowing for smooth landing regions and traversing paths. The only requirement for landing in this region is to be within 1-2 kilometers of the canyon edge, allowing landing along any point of the canyon. Upon closer inspection of the region in the small white box in the above picture of Coprates Chasma, the layered regions are very distinct.

Table 3. Site Selection Examples

Canyon	Slop	Advantages	Disadvantages
Ophir	TBD	Smooth landing site	Not much data
Coprates	75 - 85	arge landing rea. Has a teep sloped anyon wall.	Not much data on smoothness of landing area,
Gangis	First 400 m up to 60, landslides near bottom of canyon where slope is minimal	rater bed is ood site for ander xperiments. rovides mooth, flat ath from ander to liffhanger ite.	Small area for landing (crater only 27 km wide) which may make precise landing very difficult
Candor	TBD	TBD	Not much data

These regions of layers are the primary mission of the Cliffhanger to inspect and remove samples, pictures, and other experiments from the canyon edges.

A second example of possible landing site is the large crater located on the boundary of Aurorae Planum and the southern rim of Gangis Chasma (approximately 48 degrees West and 8 degrees South) shown in Figure 13. This area is located near the eastern region of Valles Marineris.

6. Conclusions, Recommendations

Future Studies and Lessons Learned

The ideas presented in this report are, of course, only preliminary investigations into the areas of rope-climbing robots and long-term observatories on Mars. Successful and cost effective completion of either mission objective will require much research into each of the design thoughts given by the team, no matter how basic or complex they may seem. It will also be necessary to make final decisions in the areas of experiment selection and redundancy versus cost.

Rope-Climbing Robotics

One of the most important areas for further study lies in the area of rope-climbing robotics. Many of the designs presented in this report have not been given more than the most rudimentary practical investigation. It will be vital to conduct extensive testing of these designs in a terrestrial setting to see, for example, how the cliffhanger will perform when exposed to various canyon wall angles and surface features. The robot has been designed to have the capability for locomotion at any angle (including somewhat uphill slopes) but maximum effective motion will be achieved at descent angles from 70-85 degrees. Further testing could suggest ways to make the robot more mobile on flat surfaces without sacrificing its descending capabilities. The usefulness of these robotics tests would extend far beyond the canyon walls of Mars. As stated earlier, many terrestrial applications exist for climbing robots—these uses will facilitate finding support and funding for such tests.

Site Selection

The results of these tests would also assist in another key area for successful primary mission completion. By characterizing the exact strengths and weaknesses of the final cliffhanger design, it will be possible to make a more effective site selection. Detailed, high-resolution images and reliefs of possible landing sites will be necessary in choosing the site that is most clear of debris with the most consistent angle of descent down the canyon wall. The suggestions put forward by this report are dependent on relatively low-resolution images without relevant MOLA data.

Power for the Mission

There is also a need for further investigation into the area of power production. While solar panels and batteries are capable of providing the power necessary for the mission, the team feels it is necessary to add a “safe mode” of operation to the lander and rover for the secondary mission. In this mode, the rover will return to the bay in which it was transported to the planet and the lander will retract all unnecessary instrumentation. It will also be necessary to retract the solar panels and survive solely on stored battery power. In long-term emergencies, such as lengthy dust storms, which can blanket an area for months, this situation would be far from ideal. So the team proposes adding an additional power source capable of at least keeping the base warm enough to prevent equipment damage. Several power options are available for this, including combusting reactive metals such as lithium for both heat and power and a nuclear power source such as the RTG’s employed by NASA in the past. The nuclear engine would seem to be the best choice based strictly on performance criteria, but investigation into public policy and ecological concerns will be necessary before such a choice can be implemented.

Instrumentation for the Mission

Finally, it will be extremely important for scientists to carefully review all that is known or suspected of the evolutionary history of the planet. It will be possible to include instruments specifically designed to test theories and models of Martian history as well as instruments to make more general measurements. The cliffhanger was created as a modular design, allowing a variety of experiments to be performed while the robot descends the canyon walls. And, because samples will be returned to the landing site, far more in-depth studies will be possible through instruments contained in the lander.

These and other design and safety factors must be taken into account before the designs for the mission can be finalized. There were, of course, lessons to be learned from past successful and failed planetary missions but the adventurous nature of this particular mission will require research in entirely new directions. But the magnitude of the questions answered by this mold-breaking mission combined with its effect on the design of future manned missions and use in terrestrial applications will ensure that this research is not completed in vein.

7. OUTREACH

The following university and public activities were executed during the project to raise the academic and public awareness of the importance of space exploration and Mars missions:

December 3 , 1999, Penn State Mars Polar Lander Event and Mars Society MarsFest. Presentation and website development during worldwide celebration of space exploration on the occasion of America's return to Mars on the Mars Polar Lander mission. Events was held around the world by Mars Society chapters and other participating organizations for public outreach and to promote understanding Mars and Space Exploration.

April 7-8, 2000

HEDS-UP presentation at regional student conference for the American Institute of Aeronautics and Astronautics on April 7-8 at Penn State. http://navier.aero.psu.edu/~aiaa/conf/

April 8, 2000

HEDS-UP presentation booth. Space Day event at Penn State organized by the PA Space Grant Consortium (PSGC) for all Penn State groups who are involved in space-related research and education to exhibit information about their programs at this public event. Saturday, April 8, 2000, from ~11:00am to 2:00pm in the Alumni Hall of the HUB/Robeson Center.

April 26, 2000

HEDS-UP presentation at Penn State forum to discuss the formation of Space Colonization Institute at Penn State.

April 29, 2000:

HEDS-UP MARS ROBOTICS event at Penn State. Time and place: Saturday, April 29, 2000 from 10:30 a.m. to 1:00 p.m. in the 108 Wartik Lab. During the event, students outlined future robotic Mars missions to help the Human Exploration and Development of Mars.

August 10-13, 2000

Presentation is being planned at the International MARS SOCIETY Convention. The Third International Mars Society Convention, August 10-13, 2000 at Ryerson Polytechnic University, Toronto, Canada.

Mars Society and Mars Interest Groups: The basic concepts approached during the project were consulted and discussed with PSU Mars Society members and other departments like Astronomy, Aerospace, Mechanical, and Electrical. A lot of other ideas, not mentioned in this report, were discussed with these groups.

World Wide Web: The www web page; http://www.engr.psu.edu/ee/pub/ee497d/ was maintained on a daily basis throughout the project to raise the academic and public awareness of the importance of space exploration and Mars missions. All the major research topics of the project were highlighted and discussed. The web site is linked to all Mars and Space Exploration interest groups like for example NASA sites, Mars Society http://www.marssociety.com group, Mars Missions web page http://marsweb.jpl.nasa.gov, Mars Exploration; http://cmex-www.arc.nasa.gov, and others.

Publications:

All reports submitted by Penn State HEDS-UP team members are published on our Web Site as mentioned in the next paragraph. All report contain much more references covering the science of Mars and robotics.

8. REFERENCES

Student Papers published at Penn State HEDS-UP Website

http://www.engr.psu.edu/ee/pub/ee497d/

[1] Michael Schrader, "Mars in the Universe"
[2] Kevin F. Sloan, "Water On Mars"
[3] Carlos A. Mosquera, "The Atmosphere of Mars"
[4] Shubh Krishna and Jean Hsu, "Seasons on Mars"
[5] Joseph Yagloski Jr. and Christian Feisel, " Mars Geology and Volcanic Activity"
[6] Chris Carlins, "Mars Interior"
[7] Brian Sosnowchik and Nikki Thornton, "The Biology of Mars"
[8] Ben Weber, "Facts on the Polar Regions of Mars"
[9] Alysha Holmes and Mike Jordan, "Mars Future - Terraforming"
[10] Michael Graham, "Mars Interest Groups and Outreach"
[11] Joe Fledderman, "The Surface of Mars"
[12] Gregg O'Marr, "The Surface of Mars"
[13] Taite Merriman, "Mars Maps"
[14] Gregg O'Marr, "Locomotion: Legs and Artificial Muscle"
[15] Ben Weber, "Robotic Locomotion"
[16] Brian Sosnowchik and Jean Hsu, "Actuation Devices"
[17] Joe Fledderman and Chris Carlins, "Viable Uses for Sensors on a Future Mars Mission"
[18] Kevin Sloan, Michael Schrader, Shubh Krishna, "Navigation on Mars"
[19] David Borowski, Mike Jordan, Ben Webber, "Resource Production on Mars", to be published.
[20] Joseph Yagloski, Chad Laufer, Christian Feisel, Joe Fledderman, Ben Webber, "Robotic Experiments", to be published
[21] Mike Graham, Nikki Thorton, Taite Merriman, "Science Experiments on Mars"
[22] Christian Feisel, Chad Lauffer, Joseph Yagloski Jr., "Building Robot Model"
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