MICROROVER RESEARCH FOR EXPLORATION OF MARS

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ABSTRACT

There is great interest in the science community to explore Mars by using microrovers that carry several science instruments and are capable of traversing long distances [1]. NASA has planned six additional missions to Mars for 2001, 2003, and 2005. There is an excellent chance that rovers will be utilized in some of these missions. Such rovers would traverse to sites separated by several kilometers and place instruments against outcrops or loose rocks, search an area for a sample of interest, and collect rocks and soil samples for return to Earth (2005 mission). Our research objectives are to develop technologies that enable such scenarios within the mission constraints of mass, power, volume, and cost.

This paper details the current capabilities and building blocks of the developed research system and describes our near-term plans to expand the system capabilities.

1. INTRODUCTION

Scientists [2] have three main objectives in exploring Mars: to search for evidence of past or present life, to better understand the climate history of the planet, and to determine the solid planet and find out what resources it provides for future explorations. These objectives can be addressed by performing remote experiments on the atmosphere, the soil, and the solid planet. Stationary landers [3] will provide excellent scientific data characterizing the atmosphere and the soil resulting in information on the climatic history of the planet. Both the atmosphere and soil are likely to be well mixed and accessible at most sites and so can be efficiently characterized without significant mobility. However, the atmosphere and the soil have serious drawbacks for understanding long term climate and biologic issues. They are both cumulative records, each representing a single point on an evolutionary path. In contrast, the rock record is one of discrete events whose time sequence can be reconstructed. The solid rock record has highest potential, therefore, for providing unequivocal evidence for past life, past climate, and presence of water in the past.

To enable such remote experiments, scientific data must be obtained from the soil, atmosphere and rocks in an area near the landing site. Due to the lack of high resolution orbital images and the landing error ellipse, it is highly desirable that mobile systems be used to reach different areas to conduct scientific experiments. For sample return missions, a mobile rover can collect small amounts of rock and soil samples from different areas for the returning spacecraft.

The Mars Pathfinder Rover called Sojourner [4] represents the state-of-the art in flight microrovers today. This rover will be sent to Mars in late 1996 and will arrive on Mars in July of 97. Sojourner is the first rover to be deployed on Mars and as such its mission is limited to minimal traverse and science activity. It will, however, provide valuable data for the design of future more capable rovers. Sojourner has very limited range (10s of meters), is not capable of sample acquisition and manipulation (i.e., soil and rock acquisition, subsurface access, pointing and burial of instruments), has limited science packages onboard, is designed for short term missions (nominal mission is less than a month), requires careful and repetitive ground monitoring and control (limited autonomy).

Our goal is to develop technologies that overcome limitations detailed above as well as to introduce new capabilities currently not supported. These are:

- Increase rover autonomy so that the number of science experiments per uplink command is increased, resulting in more science data. This involves increased autonomy for rover navigation to reach science targets, autonomous confirmation of reaching such targets, and use of sensory information to autonomously perform manipulation and science instrument placement and pointing.
- Develop the ability of the microrover to traverse long distances by integrating a celestial sensor (e.g., sun sensor) to determine rover's orientation; and by developing a deployable mast mounted camera system to send panoramic images of the surrounding area to the ground control personnel.

- Integrate representative science instruments on to the rover and develop intelligent data reduction techniques to maximize the useful science return.
- Develop onboard resource analysis and decision making capability so that maximum science is returned for the available resources.
- Develop a distributed Internet based rover interface so that scientists can provide science experiment requests and the general public can view return images immediately.
- Test and validate these technologies in realistic settings and with planetary scientist participation.

At a recently held meeting at the Jet Propulsion Laboratory (JPL), California Institute of Technology composed of planetary scientists, it was recommended to adopt the goal of developing rovers that can achieve 5 km traverse with a probability of better than 90% success rate. This committee also developed a prioritized list of science instruments that are desirable for these rovers to carry [5].

This paper provides an overview of our prototype rover called Rocky 7 and describes our near-term goals. Section 2 gives a description of the mobility system, the sampling arm, sensors, the perception system, the navigation technique, and the science instruments. Near term plans are discussed in Section 3 which elaborates on landerless operations, our plans to increase the number of science instruments and their autonomous operations, and the development of an Internet based ground control station interface. Conclusions are given in Section 4. References are provided in Section 5.

Figure 1. Rocky 7 Rover without solar panel in JPL Mars Yard

2. ROCKY 7 ROVER

In this section we provide the Rocky 7 rover configuration and detail the constituent components. Figure 1 shows

Rocky 7 in the JPL Mars Yard. Mars Yard is a 15X25 meter outdoor test area that closely simulates Mars like terrain constructed based on statistical analysis of images taken by Viking Lander I and II.

One important consideration in developing Rocky 7 has been its flight relevance. This has severely constrained its size, mass, and power. The size of the rover is dictated by the size of the payload envisioned for Surveyor missions. Rocky 7 measures 48 cm wide, 64 cm long, and 32 cm high. The wheel diameter is 13 cm. The peak power available on Mars using a solar panel is 15 watt. The flight rover is estimated to weigh less than 12 kg. Since we use commercial components on Rocky 7, its current power consumption is higher than 15 watt, but there are flight equivalent components that can reduce the power requirements to 15 watt. Figures 2 and 3 show the top and side views of Rocky 7, respectively.
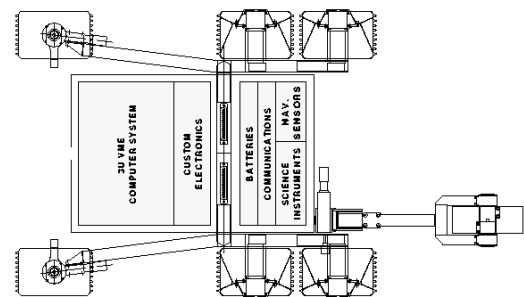

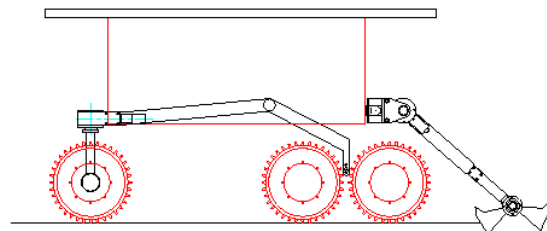**Figure 2.** Schematic drawing of top view of Rocky 7 rover.

Figure 3. Schematic drawing of side view of Rocky 7 rover and manipulator arm

2.1 Mobility System

The mobility system is a modified Rocker-Bogie design used in previous rovers at JPL [6]. It consists of two rockers (hence the name Rocky) hinged to the sides of the main body. Each rocker has a steerable wheel at one end and a smaller rocker at the other end. Two wheels are attached at the end of each of these small rockers. The main rockers are constrained in motion via a lever which is hinged at the end of the main body and its two ends are attached to the end of main rockers. This mechanism provides two important mobility characteristics for the rover. First, a wheel can be lifted vertically while other wheels remain in contact with the ground. This feature provides rock climbing capability to the rover. Rocky 7 can climb rocks 1.5 times its wheel diameter. Second, the vehicle can climb over rocks that span the width of the vehicle, even if a rock almost fits snugly between the front and middle wheels, using the smaller rocker and the two-wheel arrangement on the main rocker [6].

Unlike its predecessors Rocky 3 and 4 that had four steerable wheels, Rocky 7 has only two. This configuration has been selected to reduce the number of actuators used in the rover mobility from 10 to 8 with an option to further reduce it to 6 (the two wheels on each small rocker can mechanically be linked to each other). Although, this restricts the rover's turning capability, i.e., the rover cannot turn exactly in place, Rocky 7's ability to navigate forward and backward reduces the need for turning in place moves (see Section 2.4).

2.2 Sampling System

One significant improvement over previous Rocky series rovers is the incorporation of a sampling device on Rocky 7. The savings in actuators achieved by reducing the number of steerable wheels are used to develop the sampling system. This lightweight (700 gm) sampling arm consists of a two-DOF manipulator (32 cm long) that is attached to the front of the rover and can reach 10 cm below the ground surface. When folded, it is in a horizontal position against the front of the rover. The arm has a two-DOF scoop mechanism and is designed to both dig and carry the samples. When scoops are rotated 180 degree backward the arm can grasp objects using the back side of the scoops.

In addition to sampling function, the arm is used to deliver light to an optical fiber via a pair of mirrors. This is accomplished by configuring the scoops to a position and exposing a normally closed hole. The optical fiber carries the light (image) to a point spectrometer located inside the rover chassis (see Section 2.6).

2.3 Sensors

Several sensors are used for navigation. A rate gyro is used to keep track of rover's orientation, which needs to be updated periodically due to its drift. In addition an accelerometer is installed to provide pitch and roll information. The wheels are equipped with encoders for precise servo control and to estimate rover's position. The position of the front lever and the small rockers are sensed by potentiometers and can be used for rover's state estimation. A sun sensor has been developed by Lockheed Martin to provide an absolute heading information. The rover is equipped with four (extendible to eight) CCD cameras, two at each end, for the perception system discussed in the next section.

2.4 Perception System

To simplify the perception system hardware, Rocky 7 uses only a passive stereo vision [7] for hazard detection unlike its predecessor that used a laser striping system in conjunction with multiple monocular cameras to detect obstacles. The stereo vision system uses a pair of cameras with wide angle lenses to allow viewing of both the manipulator and its actions as well as to permit imaging of rocks and other hazards extending from near the rover to a little above the horizontal.

A pair of frame grabbers is used to obtain two 256X240 images. These images are warped to remove radial distortion and then reduced to 64X60 images by an image pyramid transformation. The Laplacian-of-Gaussian images from the pyramid are processed on-board by a correlation algorithm to develop a stereo disparity estimate which is transformed by means of a camera model to a range map.

Using this map a decision is made as to presence or absence of "step" hazards that are too steep for the rover to climb over, or of "high-centering" hazards that could cause the rover body to get stuck on a rock. In the current implementation, which has not been streamlined for speed, it take roughly 10 seconds to process one pair of images and determine whether or not there is a hazard in the near vicinity of the rover using an onboard 68040 CPU.

One important advantage of using passive stereo vision based perception is that the information obtained is based on higher resolution image processing than the laser striping system used on Sojourner [4]. This allows for detection of certain shaped rocks that could be missed by the laser striping system. There are also possible disadvantages to the stereo vision based perception system since featureless objects such as sand dunes or "bland" rock walls may not be detected.

Another advantage of stereo vision system is that it is easy to extend the system capability by adding additional cameras to the back side of the rover and use the existing infrastructure (i.e., frame grabbers and software) to perform collision avoidance.

2.5 Navigation System

Rocky 7 navigation strategy is based on operator waypoint designation and autonomous behavior based navigation to move to the specified targets [8, 9]. Operation starts with a command to the lander which has a pan-tilt mounted pair of stereo cameras to take a panoramic image of the scene by obtaining several overlapping images. These images are then processed by a similar stereo vision software to obtain terrain maps on the ground. An interactive software allows one to select specific points (locations) on one of these images using a mouse. The software returns the position of this location as calculated by the stereo vision system and displays the coordinates of the point. If no valid coordinate exists for the particular point, the software indicates this to the operator. The operator continues this operation and builds a path which deems to be safe for the rover to traverse through in moving from its initial position to the target location.

Before each move, the takes a set of images and process them onboard and determine if there are obstacles that it must avoid. If there is no obstacle it moves a short distance and then stops and repeats the same operation. If it determines that there is an obstacle, then it turns away by a fixed amount to the right or to the left depending where the obstacle is. The rover uses its odometry and the rate gyro to update its position. For the next move, it performs an obstacle detection and makes sure that there is no longer an obstacle. When clear, it plans a path that takes the rover to the original waypoint. In order to stay away from the obstacle, this path is constructed to be an arc of a large radius. If the rover turns away from an obstacle and then detects another obstacle (or the same one), it keeps turning away until it does not detect any obstacles. It then plans a path to the waypoint as described before. However, if the rover turns 360 degrees and does not find a collision-free path, it gives up and sends a message to the operator.

If the rover detects an obstacle to its far left (or right) and turns away and then detects another obstacle this time to its far right (or left), it will go through the mid point of these obstacles. If situation persists, it will conclude that it is not safe moving forward and will back up. Another set of cameras mounted on the back side of the rover can make the backing up operation much safer.

2.6 Science Instruments

An important objective of our research in developing rovers is to understand not only the mobility, navigation, and control issues, but to also consider problems associated with the integration of science instruments, their onboard operation and data reduction.

Currently Rocky 7 has a point reflectance spectrometer onboard with its fiber optic path integrated into the rover manipulator. This allows the spectrometer to be pointed at rock/soil targets from many different angles. Also included on the manipulator is a calibration target for taking reference data for the current illumination. In the near future a laser will be added to the fiber optic path so that the point of the spectra data can be illuminated and imaged to confirm exactly where the spectral data was taken.

The spectrometer has a range of ~400-850 nm which is useful for looking for spectra of different minerals. Onboard software has been have been developed and tested which matches spectral signatures. This capability can be used to find targets autonomously by the rover.

3. NEAR-TERM PLANS

Our plans are to extend the current Rocky 7 capabilities in navigation and control, and by addition of science instruments and their autonomous operations. Current Rocky 7 operation depends on a lander for science target selection and waypoint designation. Lander provided images are used on the ground station for Sojourner localization and by autonomous image processing onborad the lander for Rocky 7. When the rover traverses far away from the lander, these operations can no longer be supported by a lander.

The scenario for the operation of the rover will consist of traversing in the indicated direction, using a sun sensor in addition to existing navigation sensors, and periodically (e.g., ~100m to 200 m) transmitting panoramic images to the ground station. These panoramic images will be obtained by a pair of cameras mounted on a stowable mast that is carried by the rover (see Section 3.3). The ground station will provide new commands to either to continue to traverse in the same direction or to change direction. If the site is of interest to scientists, site survey commands will be issued. For each site survey, a panoramic image will be used to designate science targets and to specify science experiment parameters (such as angle of pointing a science instrument relative to a target, instruments distance from a target, and duration of data acquisition, etc.). The rover will then autonomously perform the requested science experiment. Success of each science

experiment will be confirmed by the rover autonomously via executing specific tests for that experiment.

3.1 Landerless operations

At the survey site, the rover will provide a panoramic image. We mentioned previously that the ground station will use this panoramic image to select science targets and designate waypoints to several targets. Due to infrequent communication opportunities to the ground station (typically once every 24 hours) it is highly desirable to perform several science experiments per uplink command. Since dead reckoning errors grow with time and distance, a technique must be used to ensure that the rover will reach its targets. Since there will not be a lander present, the rover's position cannot be updated using a lander.

The strategy for rover localization is to designate several rocks near a science target (or waypoint) and then use rover stereo vision system to match rocks near the point to these preselected rocks. The matching is done using both approximate rock position, based on dead reckoning, and matching rocks using their height. When a good match exists, then the rover can determine autonomously its relative position to the rock constellation.

3.2 Additional Science Instruments

Two other instruments are currently being added to Rocky 7. The first is a mast mounted stereo imaging system. This will serve to gather panoramic imagery to support mission operations and target selection. This effectively replaces the lander cameras once the rover moves out of range of lander. Although the camera will be monochrome, a filter wheel system will be used to gather broad band spectral data enabling color images to be constructed. The mast system itself is a deployable/stowable system so that it does not constantly shadow the solar array and does not have to support dynamic loads while the rover is moving. The current design for the mast system includes three degrees of freedom in a torso/shoulder/elbow configuration enabling the cameras on the end to be positioned more than a meter off the ground as well as being able to pan and tilt the cameras to get the desired imagery. The mast configuration is shown in Figure 4 in three different positions: stowed, partially deployed, and fully deployed.
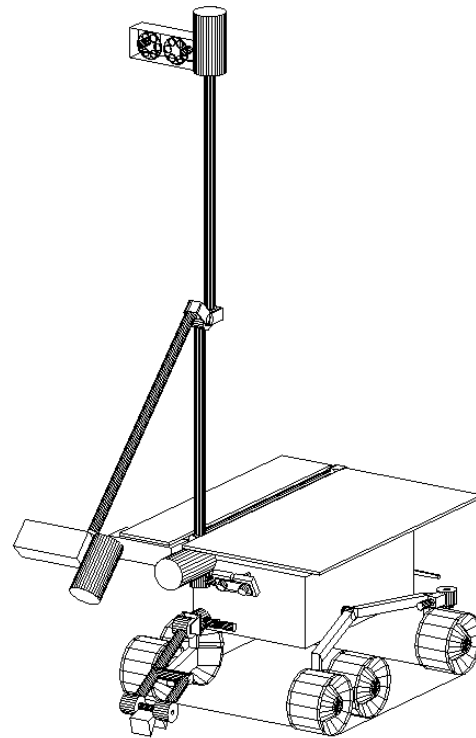

Figure 4. Rocky 7 with added mast shown in three positions

The other instrument being added to the rover system is a close-up imager that will use a monochrome camera and active lighting source. This will be packaged as a "dummy" instrument (500g soda can) representing an APX or Mossbauer spectrometer which would have to be placed against a designated target. The instrument will be mounted on the end of the mast and the mast degrees of freedom will be utilized to position instrument against rocks in front of the rover. Passive compliance will be used to allow the instrument to orient itself normal to the target surface and contact sensors used to confirm placement.

On-board science data processing will be explored in the future both in terms of data compression to meet communication bandwidth constraints as well as on-board data analysis. Although it is desirable to return all raw data and guide the rover during each step of operation, communication limitations require higher autonomy. Therefore, providing the rover with the capability to utilize science data in subsequent operation to maximize science data return is highly desirable. For instance the rover could potentially use an uplinked spectral signature to automatically find multiple samples of interest via spectral matching and carry out in-situ analysis all in a single uplink command.

3.3 Increased Autonomy

Mission science return is a function of rover's autonomy. The more autonomous operations there is the more science can be returned for each day's operation. This applies to both navigation and science instrument placement and pointing operations. The remote system must therefore be highly autonomous, automatically executing tasks and recovering from failures. Furthermore we believe that this autonomous operation should be driven by the science mission or science tasks which must be performed.

A rover command and control language explicitly in terms of the science tasks (e.g., go to specific rock and take close-up image and APX spectra) is currently being developed. The language is being written to support easy addition of new commands as well as sequence branching (e.g., if rock has specified spectra then take those). We hope to demonstrate the ability of the control system to autonomously sequence through 3 or more science tasks as well as monitor the success or failure of each task.

We will also develop failure recovery and replanning algorithms enabling the rover to retry or abandon failed tasks. We will introduce resource monitoring and resource based planning to efficiently achieve as many science objectives within a command cycle as possible. Resource constraints modeled will include: time, power, data storage, and downlink capacity.

In the lower level, we are developing tools for autonomous sampling and science instrument pointing and placement. For example, the soil sampling operation starts by an operator designating a region where samples should be collected. The rover moves to that position and then using the vision system checks for two situations that can cause a problem for sampling operation. It makes sure that the ground is relatively level and free from texture. This reduces the probability of trying soil sample acquisition on solid rocks. The vision system also checks for possible collision between the manipulator arm and rocks when deployed. Only after these two tests indicate that the conditions are satisfied for sampling, the arm is automatically deployed and samples are obtained (note that the arm currently checks and detects the ground using its motor current to determine exact ground height).

Similarly, during science instrument pointing operations, such as positioning the arm for spectrometer data collection, the vision system is used for several autonomous operations. First, it must be determined that there is a rock as specified by the operator to perform the experiment on. Then if the rover is too far from the rock, a move must be planned to bring the rover closer to the rock. The vision system must then find a tangent plane to the rock surface. Finally, the collision detection computation must be performed to ensure that the arm will not collide with the rock when deployed. The control system then moves the manipulator arm such that the image collection for the spectrometer is done normal to the tangent plane.

3.4 Advanced Operator Interface

JPL and NASA Ames Research Center (ARC) are collaboratively developing a ground control station to remotely command the rover and receive data from it. The operational scenario is based on the rover down-linking science data and stereo panoramic image pairs. This data along with camera parameter information is used to develop terrain maps. These maps can then be utilized by a virtual reality (VR) display system developed at the NASA Ames to provide a synthetic image of the terrain. An operator can use the fly-over capability of this VR display to look at the scene to better visualize the terrain. This includes a fly-over capability allowing viewing panoramic scenes from various viewpoints and flying over multiple overlapping panoramic scenes.

In addition to VR display, we are developing a World Wide Web (WWW) based interface which consists of viewing an image taken by a rover camera. Through a mapping between this image and an elevation map discussed earlier an operator can point and click on any point on the image and obtain the coordinates of the point. This technique has been used before at JPL for target selection and waypoint designation successfully. We are developing a WEB based version of this interface with added features that will allow a scientists to select science targets in his or her home institution using any computer platform. He/she will also be able to describe the nature of a particular science experiment to be performed at that point (pointing requirements, time required for data collection, data compression, etc.). This information is then sent electronically to a central station at JPL for consolidation and verification for flight rules for next day's mission and for uplinking to the rover. Figures 5 and 6 show the interface for remote target and waypoint selection.
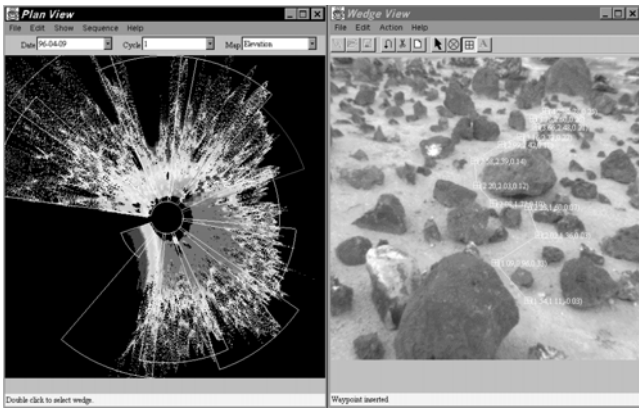
Figure 5. WEB based interface. Right image shows waypoints selected. The left image shows a top view of the elevation map generated from panoramic images. The right image corresponds to one of the wedges shown in the left image. This interface can be accessed from:
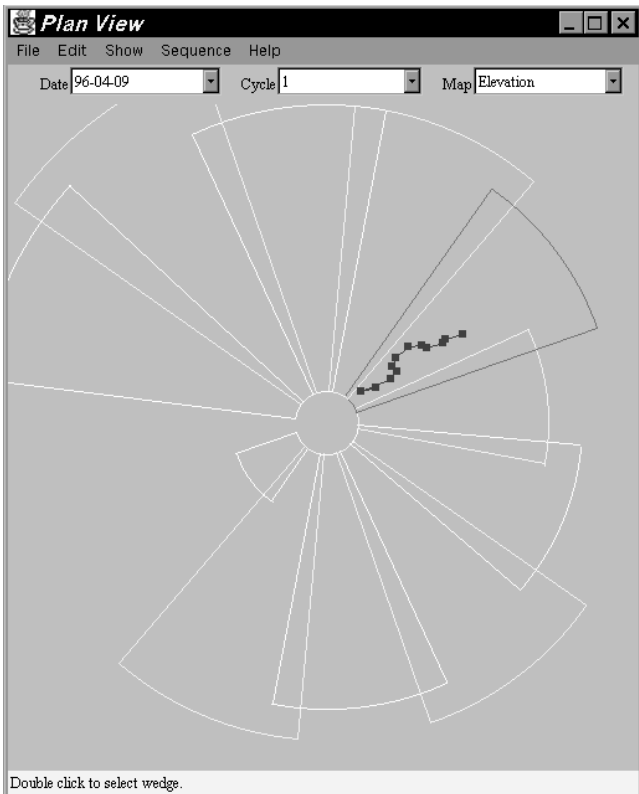***http://robotics.jpl.nasa.gov/tasks/scirover/operator/wits/index.html***

Figure 6. This image is the same image as shown in Figure 5 without the elevation map. The operator has an option of looking at the left image of Figure 5 with or without the elevation map.

Plans are also underway to provide panoramic elevation maps to clearly show the camera image in the context of the panoramic elevation map. The operator control station will also be able to show these in the context of descent imagery which is very important for scientists planning their global exploration strategy.

In the future, we will perform feature segmentation and provide feature maps to identify landmarks for rover localization autonomously.

4. CONCLUSIONS

This paper has provided an overview of research on future Mars rovers covering navigation, perception, science instrument pointing and placement, and operator interface issues. We have also detailed our plans for near future enhancements of the system. These enhancements will provide additional capabilities for long range navigation and for integration of additional science instruments on the rover.

Although this research program covers many essential elements of Mars rovers, research related to materials, space qualified computers, communication hardware, thermal insulation, advanced mobility systems, and structures are being address by other tasks at JPL [10].

ACKNOWLEDGMENTS

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