Mars Rovers: July 4, 1997, and Beyond

by *Sharon Laubach*

Introduction

Planetary scientists have a unique problem when trying to collect data: in the absence of an interplanetary manned space program, they must rely upon remote sensing techniques. An invaluable part of their arsenal is spacecraft that can study the region of interest in detail. *Landers* in particular are able to bring sensors and instruments into close contact with the planetary environment. This allows them to take direct measurements of properties such as soil mechanics and elemental composition, as well as image surface features in greater detail than is possible with *orbiters* or Earth-bound instruments. Landers, however, have the shortcoming that they are limited to a single site for study. An important addition, then, is a mobile robot which can roam over a much larger segment of the terrain and can carry *imagers* and other instruments to a variety of features spread over this larger area.

The recent Mars Pathfinder mission demonstrated the utility of such an approach. The Sojourner rover was carried to the surface of Mars by a lander. Over an area approximately 10 meters in radius, it conducted soil experiments in several different terrains, took detailed images of rocks and soils from centimeters away, and placed its on-board spectrometer on 16 distinct targets (9 rocks and 7 soil sites) [5].

Future missions plan to expand this successful technology by incorporating mobile robots (``rovers'') which are capable of traversing even larger distances, carrying their instruments to a wider variety of features and even caching samples along the way. A key requirement for these new planetary robots is greater navigational autonomy, since longer distances than in prior missions must be covered between communication with Earth. An Earth-based prototype rover, called ``Rocky7'', has been developed at the Jet Propulsion Laboratory (http://www.jpl.nasa.gov) to serve as a testbed for new technologies for future missions--in particular, the capability to traverse long distances autonomously.

The next section gives a brief overview of the Mars Pathfinder mission, and describes the author's experiences as a Rover Sequence Planner during the first weeks after the Mars landing. Next is a description of the current objectives for the Mars rover missions like those in 2001 and 2003. The fourth section describes the Rocky7 prototype rover (see also http://robotics.jpl.nasa.gov/tasks/scirover) , and the current work extending Mars rovers' abilities to navigate longer distances autonomously.

Figure 1: The Sojourner Rover

Adventures on Another Planet

The Mars Pathfinder mission (see http://mpfwww.jpl.nasa.gov/) was truly an adventurous project. Marking humankind's return to the Martian surface for the first time in 20 years, the spacecraft tested an astounding number of new technologies. This included, perhaps most spectacularly, a unique method of entry, descent, and landing (see http://mpfwww.jpl.nasa.gov/mpf/edl/edl1.html), as well as the deployment of the first mobile spacecraft on another planet, the Sojourner rover (see http://mpfwww.jpl.nasa.gov/mpf/rover.html). Pathfinder's entry, descent, and landing sequence, including the use of direct entry without orbiting first, parachutes to slow descent, and airbags to cushion the hard landing, broke nearly all of the ``rules'' established by the Viking landings on Mars. The task of the Pathfinder rover was to act as a ``mobile remote geologist,'' bringing *imagers* and instruments up close to the rocks and soils that could be seen so tantalizingly by the Pathfinder lander's cameras. The more detailed the data returned by Pathfinder, the more certain the project scientists could be in determining the compositions and morphologies of the Martian terrain. This in turn meant they could learn about the geological history of that part of the planet, and specifically about the role of liquid water on ancient Mars.

Sojourner's task, however, was a very difficult one. In order to be able to traverse the rocky terrain expected on Mars, the rover was designed with a number of unique features. Mechanically, for example, Sojourner utilizes a six-wheel ``rocker bogie'' system, which allows the rover to surmount obstacles one-and-one-half wheel diameters tall (1 wheel diameter = 13 cm), analogous to driving your car over your dining room table!

The action of the rocker-bogie system can be seen in the ``rover movie'' taken on Sol 24 (1 sol = 1Martian day) available at http://mars.jpl.nasa.gov/ops/rover_movie_sol24_S0050Q.gif (caution..this GIF is 1800K!!). The lander camera (the Imager for Mars Pathfinder, or IMP; see http://www.lpl.arizona.edu/imp) addresses the problem that it takes on average about 20 minutes for commands to reach Mars from Earth (plus another 20 minutes for confirmation). This inherent delay renders ``remote-control'' teleoperation impractical, even assuming that the ground operators have continuous use of the Deep Space Network used to communicate with spacecraft (which is not possible, due to scheduling constraints).

The Sojourner rover features limited autonomous navigation ability, encapsulated primarily in the ``Go To Waypoint'' command: ground operators specify a goal location, and the rover moves toward the goal without further instruction, avoiding obstacles and other hazards on its own. The rover captures stereo image data with its front-mounted stereo camera pair, which it also uses to perceive its environment via a laser-striping system. This system senses obstacles ahead of the rover as follows: the five on-board lasers project stripes onto the ground, and selected lines in each camera are scanned to build up a 20-point range ``image'' of the terrain immediately in front of the rover. This terrain model is then used on-board, during execution of the ``Go To Waypoint'' command, to perform hazard detection and avoidance on the way to the goal. Sojourner's sophisticated software was written in C and assembly using a Unix development environment (note: Sojourner has no on-board operating system); it runs on an Intel 80C85 processor operating at 2MHz, a choice dictated by power and radiation-hardness constraints. The ground operators' interface is Silicon Graphics Inventor ®-based. Sojourner's top speed is roughly 1 cm/sec, and the rover is only 68 cm x 48 cm, standing all of 28 cm tall when fully deployed [5 , 4].

The author had the opportunity to witness the performance of each of these elements firsthand during the first few weeks after Pathfinder landed on Mars, in her capacity as an uplink engineer on the Rover team. The Rover Flight Team comprised two distinct roles: downlink and uplink. The downlink engineers' task was to interpret data returned to Earth by the spacecraft. Members of each subsystem (e.g. mobility, thermal, power, communications, and control and navigation) assessed the state of the rover, and generated constraints to be considered in the next sol's operations. This team had to provide an initial evaluation of the state of the vehicle within approximately two hours of the end of the downlink communication session with the spacecraft. The downlink team then met with the uplink team to report their conclusions. Next, the uplink team met with the project scientists to determine the course of action for the next sol, and to hash out conflicts between desired experiments and the rover engineering requirements. Finally, the uplink engineers spent the next several hours laboriously building and documenting the command sequences, using the Rover Control Workstation (an SGI Onyx 2). A typical sequence contained 200-300 commands, detailing everything from thermal control parameters, to health status check rates, to actual instrument operation and traverse instructions. The traverse commands, in particular, necessitated an intensive building process: the designated ``rover driver'' donned LCD shuttered goggles in order to scrutinise a 3D display of actual Martian terrain derived from stereo data from the IMP cameras.

Figure 3: Red/Blue Anaglyph of Martian Terrain.

(See the image, a red/blue stereo anaglyph, to get a feel for the Martian terrain--you will need red/blue glasses to see the image in 3D.) The driver utilised a 3D graphic icon modelled on the rover to plan Sojourner's movements; in times when caution was necessary, the plan included such detailed instructions as ``turn clockwise 17 degrees, then move forward 10 cm'' to manoeuver the robot through tight spaces. In the most relaxed cases, the driver needed to ``connect-the-dots'' by specifying goal positions in clear areas, since Sojourner's ``Go To Waypoint'' command had only been tested for distances of several meters. Even more importantly, the distance travelled by the rover each sol was limited by accumulated dead reckoning error, which was on the order of 5-10% of the distance travelled [5]. The Sojourner rover was highly dependent upon the rover drivers' ability to localize the rover in the lander-based coordinate system at the start of each sol. The sequences were then reviewed especially carefully for errors, since (more so than with past spacecraft, whose environments were generally more predictable) a wrong command could potentially damage the rover. The rover sequence was next incorporated into a lander sequence for transmission to the spacecraft. The sequence would then at last be uplinked and received by the rover the morning of the next sol.

Figure 4: The rover at Yogi.

Sojourner would execute the command sequence during the Martian day, and that night the cycle would begin again as the spacecraft reported back to Earth with the sol's new data.

The Sojourner rover successfully operated on the surface of Mars far in excess of its design life of 7 sols. In fact, despite loss of its battery and subsequent reliance on its solar panel for power, the rover was continuing to operate up until Sol 83 of the mission, when communications between the lander and Earth was lost. As far as is known, the Sojourner rover continues to operate on its own, in hopes of re-establishing contact with Earth.

The Adventure Continues...

As the capabilities of rovers improve, they will be incorporated into future missions. In particular, scientists are interested in being able to explore more than one geologically distinct region within a single mission, which can only be accomplished by rovers which are able to function without being tied to a lander--either by communications or by navigation requirements. In addition, the next rover missions seek to address a difficulty inherent in current robotic space applications: it just is not feasible, or perhaps not even possible, to incorporate all of the capabilities of an Earth-based laboratory into a rover on Mars. Thus, while gathering as much information as possible about the Martian environment, the future rovers will also be required to analyze rock and soil samples *in situ* and then cache those samples which are deemed ``interesting'' to be brought back to Earth by later spacecraft.

Another important consideration is from an operational standpoint: because of budget constraints, future rover missions will still be handled by a very small flight team. (The Sojourner flight team is composed of on the order of 20 people.) Since the new rovers are planned to operate for an entire Earth year, as opposed to the one month extended mission planned for Sojourner, it simply is not reasonable to expect the flight team to keep as intensive a schedule as was required for Pathfinder operations. These advances necessitate rovers which are able to traverse several kilometers with enough accuracy to reach the goal specified by the project scientists, with a minimum of direction from human ``drivers.'' For example, it is expected that the rover for the 2001 mission will traverse a distance of roughly 10 kilometers total. The rovers will still be governed by commands received through the Deep Space Network from Earth, whose use will still be rigidly constrained by scheduling issues -- thus the rovers must be able to navigate several hundred meters per sol autonomously. This fact places immense demands upon the rover navigation system to be able to make significant progress through rough, rock-strewn terrains without assistance from Earth-based operators [1]. In contrast, Sojourner traversed a total of approximately 100 meters, staying within about 10 meters of the lander, and required relatively intensive supervision by ground operators.

Preparations for the Future

Figure 5: Rocky7, Mast Deployed.

In order to develop the technologies needed for these future Mars rover missions, the Long Range Science Rover task at the Jet Propulsion Laboratory (JPL) was established, with its Earth-based prototype rover, Rocky7. The rover differs from Sojourner in several ways, including being designed for Los Angeles/desert conditions and Earth gravity, as opposed to Sojourner's environment on Mars. More germane to Rocky7's role as a testbed for new technologies, the rover sports two arms, a sun sensor, and more advanced navigation and perception software, among other additions to the otherwise Sojourner-like platform. The arms comprise a short, 4 degree-of-freedom (DOF) arm with clamshell scoops for soil sampling, with an integrated optical fiber path for an on-board spectrometer; and a longer 3 DOF ``mast'' which carries a stereo camera pair outfitted with filter wheels, and another spectrometer or similar instrument.

As shown in the photo (taken in the JPL ``MarsYard''), the mast can be deployed to hold the stereo camera pair 1.4 meters above the surface, providing a panoramic view of the surrounding environment. The mast can also be used to bring the end-mounted instrument into contact with a specified point on the terrain in front of the rover, and is stowed during rover motion. It should be noted here that the ``MarsYard'' is an outdoor testing facility at JPL, built to model the Martian terrain as seen by the Viking landers of the 70's. Rocky7 also utilizes the entire image plane of the stereo cameras to derive its range image of the surrounding terrain, generating a much more accurate model of potential obstacles than is possible with Sojourner's 20-point image. Dimensionally, Rocky7 is roughly the same size as Sojourner, at 61 cm x 50 cm, standing 35 cm tall; its speed is roughly 1 meter/minute.

Figure 6: The Rocky7 Research Rover

The Rocky7 rover differs from Sojourner as well in computing power, in line with the expectation that the rovers in future missions would use a 32-bit processor operating at at least 15 MHz. Rocky7 utilises a 68060 CPU in a VME chassis, running at approximately 100 MIPS. The on-board software includes: Wind River VxWorks ® real-time operating system, and Real Time Innovations' ControlShell ® real-time object-oriented software framework and Network Data Delivery System ®. Programming for the rover is accomplished in the Unix development environment, using C++, C, and Lisp. Stereo correlation is done on-board. Finally, the ground operator interface is based on HTML/Java ® [3].

Besides acting as a testbed for integrating new technologies onto a mobile rover platform, Rocky7 serves as an important resource for algorithm research. In particular, the author is currently developing new algorithms for autonomous long-distance navigation, such as is necessary for the future missions described above [2].

Whereas Sojourner relied heavily upon the input of ground operators for both localization (updating the rover's knowledge of exactly where it is within its environment, relative to a previously-defined coordinate system) and relatively specific ``driving'' instructions, the new rovers must be able to traverse many hundred meters between communication opportunities with Earth. In addition, Sojourner was required to stay close to the lander, since her Earth-based ``drivers'' needed to be able to see the rover and the terrain from the lander's stereo cameras, and with enough accuracy to be able to specify positions within a few centimeters. However, future missions' rovers must travel far from the lander and be able to rely upon the information they can glean themselves about the environment in order to navigate and maintain an accurate model of where they are. Thus, new software is being developed which will incrementally build a path from the rover's current position to the goal.

First, the rover deploys its mast, and prepares a model of its environment from stereo panoramic data gathered by the mast cameras. The environment model is then used by the rover to determine the locally optimal path to follow towards its goal. The mast is stowed before the rover executes the local portion of the path, and then the cycle begins again as the mast is raised for another look. In this manner, the rover determines its path piecewise, where each segment is locally optimal, relative to distance travelled, for reaching the goal. In addition, the algorithm has been designed such that the rover is guaranteed to reach the goal accurately (in the case that the rover can keep an accurate model of its location in its environment, and assuming, of course, that the goal is reachable) -- a property which is not held by Sojourner's navigation algorithm. This property should reduce the number of sols (Martian days) spent moving the rover to the specific region the scientists want to explore.

Conclusion

The field of planetary exploration offers a rich environment for mobile robotics research, encompassing many complicated issues which must be tackled in order to produce successful missions. In particular, this article addressed some of the issues related to autonomous path-planning for planetary rovers. With the tools provided by improvements in these areas, mobile robots will prove to be an even more useful and robust addition to the techniques available for planetary exploration.

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