Operations and Autonomy of the Mars Pathfinder Microrover

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Abstract-- The Microrover Flight Experiment (MFEX) is a NASA OACT (Office of Advanced Concepts and Technology) flight experiment which, integrated with the Mars Pathfinder (MPF) lander and spacecraft system, landed on Mars on July 4, 1997. In the succeeding 30 sols (1 sol = 1 Martian day), the Sojourner microrover accomplished all of its primary and extended mission objectives. After completion of the originally planned extended mission, MFEX has continued to conduct a series of technology experiments, deploy its alpha proton x-ray spectrometer (APXS) on rocks and soil, and image both terrain features and the lander.

This mission was conducted under the constraints of a once-per-sol opportunity for" command and telemetry transmissions between the lander and earth operators. As such, the MFEX r'over was required total'l"y outits mission, including terrain navigation and contingency response, under supervised autonomous control. For example, goal locations were specified daily by human operators and the rover safely traversed 10 these locations. " During traverses, the rover autonomously detected and avoided rock, slope, and drop-off hazards, changing its path us needed before turning back towards its goal. This capability to operate in an unmodeled environment, choosing actions in response 1 0 sensor input to accomplish requested objectives, is unique among robotic space missions to date.

In this paper, the techniques implemented on MFEX for operations and autonomous control are described and the performance 01 this vehicle (m Mars is discussed.

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1. INTRODUCTION

On July 4, 1997, the Pathfinder spacecraft successfully landed in the Ares Vallis region of Mars. On sol 2, the second Marti an day after landing, after overcoming an initial problem with poor" lander-rover communication, the sojourner" rover rolled down the rear lander ramp onto the surface. In order to carry out its mission , traversing to sites of scientific interest, the rover design incorporated autonomous capa bilities not applied in previous planetary exploration missions. The mission called i'ot-rover" traverses to be performed nearly every sol, req uiring sequence turnaround by Earth-based operators in hours, rather than the days necessary during Viking, the previous U. S.-conducted landed mission.

This paper provides an overview of the rover mission object ives, and the implementation of the rover intended to meet those objectives. We discuss how day-to-day operations were conducted to carry out the mission. To provide context for the autonomous capabilities of the Sojourner rover, we describe the steps performed by the human operators, defining where autonomy was used and

where it was not. Then we evaluate our experience operating Sojourner during the first 70 sols on the surface of Mars.

2. ROVER MISSION OBJECTIVES

As of this writing, all rover mission objectives have been met or exceeded. These objectives included:

Cost and Schedule

The MFEX budget, including design, development, implementation, and operations, was $25M. All critical delivery deadlines for integration of the rover elements with the Pathfinder mission were met, culminating in the launch on December 4, 1996.

Mass

The mass allocation for the rover and its lander-mounted support equipment (tie-downs, rails, ramps, and UHF radio link) was 16 kilograms, while the actual combined mass of all rover elements is 15.2 kilograms. The mass of the rover itself is 10.5 kilograms.

Rover Impact on Pathfinder Project

The interfaces between rover and lander were simplified as much as possible to reduce dependencies between the two developments. For example, there was no electrical interface between the rover and the lander. To wake up the rover during pre-launch and cruise mission phases, a reed relay switch in the rover was activated by a magnetic coil mounted on the lander petal; activation of the switch allowed the rover's own batteries to power its bus. For telemetry processing, the rover transmits already formatted packets to the lander, which then processes them in the same manner as packets generated by the lander itself.

Survivability

The rover had to survive the launch, cruise, landing, and Mars surface environments to which it would be subjected.

Surface Operations Objectives

Rover mission success was dc.lined primarily by the accomplishment of the surface operations objectives. One complete set of technology experiments, including soil mechanics, material adherence, and w'heel abrasion, together with one APXS rock data collection, and an image of the lander to assess its post-landi ng conditio n, have been defined to constitute 90% of mission success. The remaining 10% is achieved by completing additional sets of technology experiments, APXS data collections, and imaging activities.

Operating Range

The mission plan called for the rover to operate primarily within 10 meters of the lander; this is considered the effective limit of usefulness of the lander stereo images for directing the rover and identifying sites of scientific interest. If desirable destinations for the rover are identified further from the lander (in particular during the extended mission), then the rover may be commanded to travel as far as the lander's horizon. The rover's design allows it to drive several hundred meters from the lander before passing out of communications range. The software design will enable it to respond to communications loss in one of two specified ways: 1) stop and back up to re-establish communication, or 2) continue executing its sequence, which will bring the rover back into communications before it completes. (If human error results in a sequence that ends with the rover outside of communications range, an onboard contingency sequence will be triggered, causing the rover to drive toward the origin of its lander-centered coordinate frame.) While this long distance driving is feasible due to the rover's architecture, the rover's hardware has been qualified to support up to 100" meters of traverse on the Martian surface.

Lifetime

The rover's prime mission has been designed to allow the rover to accomplish its surface operations objectives in the first seven sols of operations. In addition, no element of the rover's design should preclude its operation for a full 30 so] extended mission, during which greater risks may be taken. The only exhaustible resource (other than normal wear) is the non-rechargeable battery; the rover is capable of performing its entire mission, with the exception of night time APXS data collection, even if the batteries are unavailable after landing.

3. ROVER DESCRIPTION

The rover design and implementation has been described previously in [1], [2], [3], [4]. The MFEX rover is a six-wheeled robotic vehicle that is 68 cm long by 48 cm wide, standing 28 cm high when fully deployed (see Figures 1 and 2). In this configuration, it has a ground clearance of 17 cm.

The mobility subsystem consists of a 6-wheel drive, 4-wheel steerable, rocker-bogie mobility chassis. This configuration allows the vehicle to surmount obstacles 1,5 wheel diameters in height. The rover's speed is approximately 0.4 meter/minute in nominal terrain.

The rover computer possesses a single CPU, an Intel 80C85 operating at 2 Mhz, processing 100" KIPS. Four types of memory are incorporated into the electronics boards: 16 Kbyte PROM, 64 Kbyte radiation hard RAM, 176 Kbyte EEPROM, and 512 Kbyte RAM, addressable in 16 Kbyte pages. Two d(luhlc-sided boards implement all processing and power conditioning/distribution.

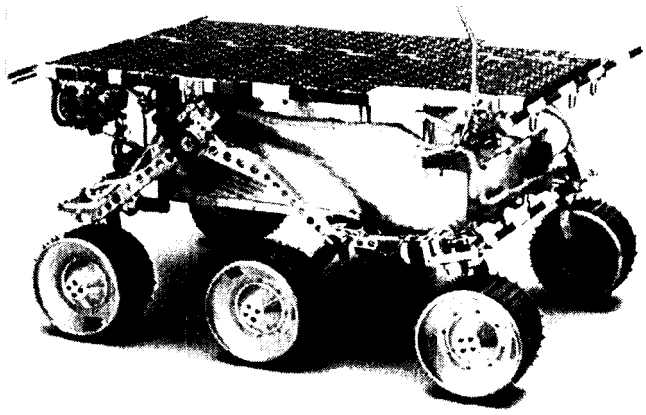

Figure 1. MFEX Rover

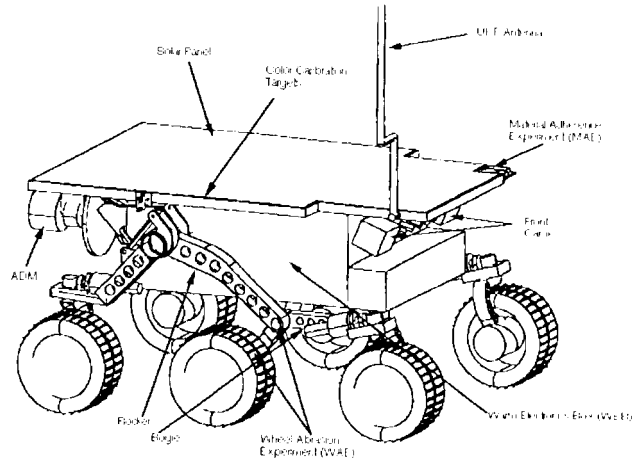

Figure 2. Major Elements of the MFEX Rover

Black-and-white stereo cameras on the front of the vehicle support hazard detection and science/operations imaging. The image size for each camera is 768 x 484 pixels, with a 4 mm, wide-angle lens providing a field of view of 127° x 94° and a resolution of 3 mradians/pixel. Each camera is mounted about 25cm above the terrain surface. A single color rear camera is used primarily for APXS target documentation.

Power for operations is supplied by a Gallium Arsenide (GaAs) solar panel providing 15W peak; primary (non-nonrechargeable) batteries enable night operations of the APXS instrument, provide extra power for mobility if needed in difficult terrain, and serve as a backup in the event of solar panel failure on landing.

A pop-up antenna is located at the edge of the solar panel. Communications between lander and rover is via UHF radio modems with a raw data rate of 9600 bits per second. Overhead for the link results in an effective data transfer rate of approximately 2 Kbits per second. Maximum separation between rover and lander for communications is 500 meters.

To protect the onboard electronics and batteries from the temperature extremes of the Martian surface, they are housed in the Warm Electronics Box (WEB). The WEB is of face sheet and spar construction, with solid silica aerogel insulation. Heating of the WEB occurs as a consequence of normal daytime operations, and by channeling excess available solar power to internal heaters. The WEB cools overnight, then begins to warm again in the early morning when the rover powers on. This strategy maintains the electronics in the ±40°C flight allowable temperature range for the duration of the mission.

Onboard experiments include the material adherence experiment (MAE) supplied by the Lewis Research Center (LeRC), which measures solar panel output; the LeRC wheel abrasion experiment (WAE) on the center wheel and bogie, which investigates the abrasiveness of the Martian soil; and the APXS, which determines the elemental composition of rocks and soil (provided by the University of Chicago and the Max Planck Institute in Mainz, Germany). Other experiments rely on the rover's imaging, engineering, and navigation sensors to generate data necessary for analysis.

4. Surface Operations Scenario

The rover operations team prepares one command sequence per sol (one Martian day). The design of each sequence is based on a combination of 1) the rover state assessment provided by the Rover Engineering Analysis Team, 2) the science and technology experiment requests from the Experiment Operations Team, and 3) the feasibility of the requested operations given the trafficability of the Martian terrain and the safety of the vehicle. The uplink team designs a sequence to fulfill as many of the science and technology requests as possible while maintaining the health of the rover.

On a given sol, there is usually only one opportunity to uplink rover and lander command sequences. This opportunity corresponds to early- to mid-morning of the Martian day.

Telemetry is commonly downlinked during three periods per sol. The first downlink occurs just prior to the morning uplink. The mission operations team has a short time to

with both an accurate indication of where it is (including where it is pointing) and where to find its destination.

Proximity hazard detection is performed using the forward cameras and five laser stripers. Every seven centimeters of traverse, the rover stops and executes a sensing cycle. The rover captures an image both with and without a laser active. Selected scanlines from each image are differenced to locate the laser spot in the scene. (Figure 3 shows the infrared laser stripe as seen by the rover during surface operations.) If the terrain is flat and level, the laser spot with be visible in a known position along the scanline. Deviations from flat and level ground will cause the laser spot to slide along the scanline, indicating a rock or depression. If the spot cannot be found in the difference image, a significant drop-off may exist. Repeating this process for 5 lasers and four sets of scanlines per difference image generates a set of 20 terrain height measurements. Height differences between adjacent measurements can indicate a rock or hole; sufficient height difference between the lowest and highest measurements in the set indicates a steep slope. False hazard detections can occur if the camera view of a laser spot is blocked by a craggy surface, so ignoring small numbers of data drop-outs is possible by modifying parameter settings in appropriate terrains. During outdoor testing, as well as operations on Mars, the rover has commonly been directed to accept up to three data drop-outs before initiating hazard avoidance behavior.

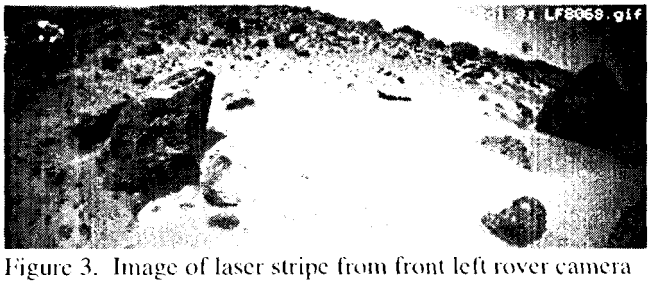

Figure 3. Image of laser stripe from front left rover camera

The geometry of the laser stripes has been arranged so that obstacles can be detected to the sides of the rover traverse direction at sufficient range to validate the rover's turning circle. This means that the rover will nominally maintain enough free space around itself to allow for avoiding obstacles detected ahead of it by turning in place and driving forward. This avoids the necessity to drive backwards, since the rover has no proximity hazard detection to the rear. If the density of hazards in the terrain is too high to permit the vehicle to maintain a clear turning circle, a "thread the needle" approach can be enabled by parameter setting adjustment. This technique permits the rover to drive between obstacles that are just further apart than a vehicle width. If the rover traverses a specified distance without finding a clear area in which to navigate (i.e., finds itself in a box canyon), it will back up straight to the point at which the "thread the needle" behavior was triggered, and then try another direction.

We have implemented several navigation safety features to protect the rover during waypoint traverses:
To ensure that the rover does not inadvertently traverse beyond communications range, it stops periodically (about once per vehicle length of traverse) to perform a "heartbeat" communications test. If the lander responds, the rover resumes its traverse. Otherwise, the rover retreats 30 cm, turns 45 degrees, and attempts to reestablish contact with the lander.

The lander itself is a potentially serious hazard to the rover. Cleats on the rover's wheels can catch airbag material, possibly permanently entangling the vehicle. A settable parameter permits the human operators to specify just how close to the lander the rover is allowed to go. This virtual hazard is triggered only if the rover is within the hazard radius and driving towards the lander. If the rover is inside the danger zone, but driving away from the lander, it will perceive no hazard. Again, depending on parameter settings, the rover will either autonomously avoid the lander, or abort the remaining traverse.

Contact sensors are located on bumpers on the front and rear of the rover solar panel, and on the lower front body of the rover. Additional contact sensors are incorporated into the APXS deployment mechanism, which is located at the rear of the rover. If an obstacle in the rover's path is not detected by the proximity hazard detection system, triggering any of the bumper contact sensors with either abort the trial or else cause the rover to back up, turn, and avoid the hazard.

If a specified waypoint destination is not reached within the time allotted in the command, the command will time out, setting an error flag. This prevents the rover from continuing unproductive attempts to achieve an unreachable goal. Depending on the parameter settings in the sequence, any remaining traverse commands will be skipped (since the rover is not where it was expected to be), or the rover will continue on to the next specified location, which may be reachable.

The "Find Rock" command allows the rover to zero in on a rock target at the end of a traverse, autonomously correcting for possible dead reckoning error. The usual strategy to reach a specific rock for APXS data collection is to first traverse to the vicinity of the target via one or more "Go to Waypoint" commands. Once there, the rover is commanded to execute a "Turn Toward" the expected rock location, so that the rover is now facing in the direction the rock is most likely to be found. (The "Go to Waypoint" command does not specify the final heading of the rover at the end of a traverse.) The rover then executes a "Find Rock" command specifying coordinates beyond the rock's actual position. The "Find Rock" executes in the same way as a "Go to Waypoint," except that the first time a rock hazard is found during its traverse, the rover will stop, then turn in place while using its hazard detection sensors to determine the

extent of the object, and finally turn to face the center of the rock.

To provide full flexibility lot rover control, low" level motion commands are available. The "Move" command directs the rover 10 drive forward or backward with fixed w'heel steering angles for a specified number of centimeters. Variations of the "Turn" command allow operators to specify relative turns, turns to absolute heading, and turns to face a particular coordinate location in the "surface-fixed frame." Additionally, selected hazard detection capabilities can be disabled during "Go to Waypoint" commands if a specific circumstance so indicates.

Contingency Scenario Responses

Earth to Lander Command Loss--The Mars Pathfinder mission planners prepared for the possibility of loss of communications with the spacecraft immediately after landing. (Fortunately, to dale, we have experienced no long term loss 01 communications during the mission.) If a two-way 10ss of communications had occurred, then no surface mission would have been possible (or any results of such a mission would never be known). }l(m'ever', if only the receiver on the lander had failed, then telemetry from the spacecraft would still be received on the ground; only the opportunity to command the spacecraft (and rover) would have been lost. In Order' to perform a useful mission under such a "command loss" scenario, n Back up Mission Load (BML) was designed and uplinked to the spacecraft during the cruise mission phase. The BML includes a set of command sequences for both the lander and the rover. The BML would have been activated after sufficient time (2 sols) had elapsed since the lander last received any sequences from the Earth. The lander would then have released sequences to the rover to stand up, deploy down the lander ramp, and perform surface operations. The lander would have transmitted telemetry, with the hope that it will be received by the DSN.

Since, in this scenario, the rover would still regularly receive new sequences, it would continue to operate in a nominal mode. The BML would have allowed some coordination of lander and rover activities during the early part of the mission. For the first few sols, until dead reckoning error accumulated to significant levels, the lander should have been able to point its camera to image the rover at its end-of-day location. When rover sequences in the BML would no longer be useful (i.e., when the rover's location was effectively unknown), the rover would have been allowed to transition to its own onboard contingency sequence.

Backup Mission Load sequences were loaded onboard the Pathfinder lander to support command-loss scenarios triggered at any tired between landing and sol 60. With the successful completion of both the lander and rover primary missions, there is no longer significant utility in a genetic mission performed via a set 01 "canned" command sequences.

Lander to Rover Command Loss--Neither the BML or nominal rover command sequences would have been effective means of commanding the rover if the UHF communications link between the rover and lander had failed on or after landing. In response to this possible scenario, the rover team developed a Contingency Mission Load (CML) which was placed into the rover's non-volatile memory before delivery of the rover to Kennedy Space Center for launch preparation.

If the failure of the lander/l(nw link had been bi-directional, then the only telemetry documenting rover activities would have been lander imaging of rover travel-ws. However, if only the command link between the rover and lander had failed, downlink of rover telemetry would still have been possible, although coordination of activities between the two spacecraft would no longer be feasible. The rover software was designed to activate a Contingency sequence if the rover fails to receive a complete command sequence for approximately two sols. The particular sequence to be triggered depends on the mission phase of the rover (i.e., prelaunch, cruise, prerelease, predeploy, primary, or extended). For example, if the rover were still (m the lander petal when the contingency mission activated, the triggered sequence would cause it to stand up, then transition to the next phase for driving down the r-drop. If the rover were already performing surface operations when the communications link failed, the activated sequence would continue surface operations, attempting to circumnavigate the lander at a range of approximately 5 meters, while finding rocks, taking APXS measurements, performing MAE, WAE, and soil experiments, and imaging. Each telemetry frame generated by the sequence would be transmitted twice. Without handshaking, the lander has no mechanism to determine into what hind of rover packet to reassemble the telemetry, so all telemetry would be classified as "unrecognized rover packets" and forwarded to the ground for reconstruction. If communications were reestablished, the rover would resume normal operation immediately when a command sequence was successfully received from the lander.

As has been the case with the Backup Mission Load, the need for the Contingency Mission Load has decreased with the continued success of the rover's mission on Mars. On sol 80, the primary contingency command sequence was replaced with a new load, which is essentially a multi-sol safing sequence. If the rover fails to receive a new command sequence after several days in contingency mode, it will then transition to the extended mission phase contingency sequence, which will cause it to attempt to drive toward the lander, under the assumption that the rover may have driven out of communications range or into a communications null region.

7. PERFORMANCE ON MARS

The overall performance of Sojourner on Mars has exceeded both design goals and expectations, as witnessed by the successful accomplishment of all rover mission objectives, and the continuation of the rover's activities beyond even the planned extended mission duration. As of sol 85, 16 distinct sites (9 rocks, "/ soil locations) had been analyzed by the APXS; over 120 MAE and 9 WAE experiments had been performed; and more than 500 images captured. The rover had traversed over 100 meters total integrated distance, nearly circumnavigating the lander (Figure 4) and averaging 2.7 meters per traverse day (Figure 5). (Several sols included no traverses, often due to either scheduled or unscheduled loss of uplink opportunities between Earth and the lander.) The rover's traverse capabilities have allowed us 10 both view features at higher resolution than would be possible from the lander's camera, and image features that cannot be seen at all from the lander's vantage point (See Figures 6 and 7).

The autonomous navigation performance of the rover on Mars has generally been equal to or better than the performance observed using the testbed I"L)\'CI' during Operations Readiness Tests on Earth.

Due to the nearly obstacle-free nature of the terrain ill the immediate vicinity of the lander ramp (see Figure '8), initial rover traverses were commanded as l~)~v-level moves, with no "Go to Waypoint" commands used. We also wished to avoid reliance on waypoint traverses until we had evaluated both the rover's dead reckoning performance in the Martian terrain, and the ability of the laser/camera hazard detection subsystem to detect the laser stripes under Mars illumination and albedo conditions,"

Rover camera images captured with hazard detection lasers powered on (e.g., Figure 3) confirmed the visibility of the stripes. The first "Go to Waypoint" command was executed on sol 12,

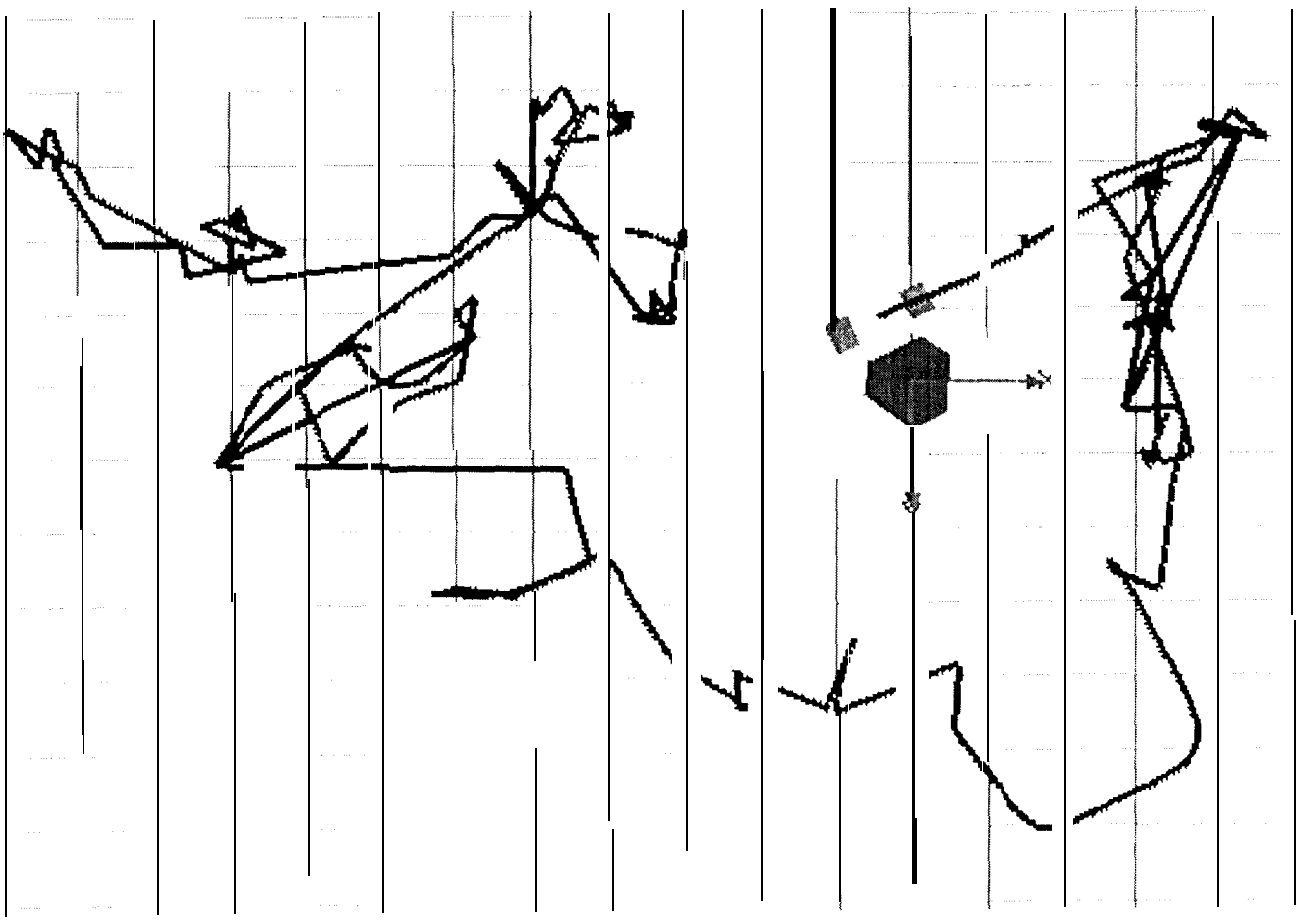

Figure 4. Rover traverses during first 85 sols
(grid spacing is 1 meter)

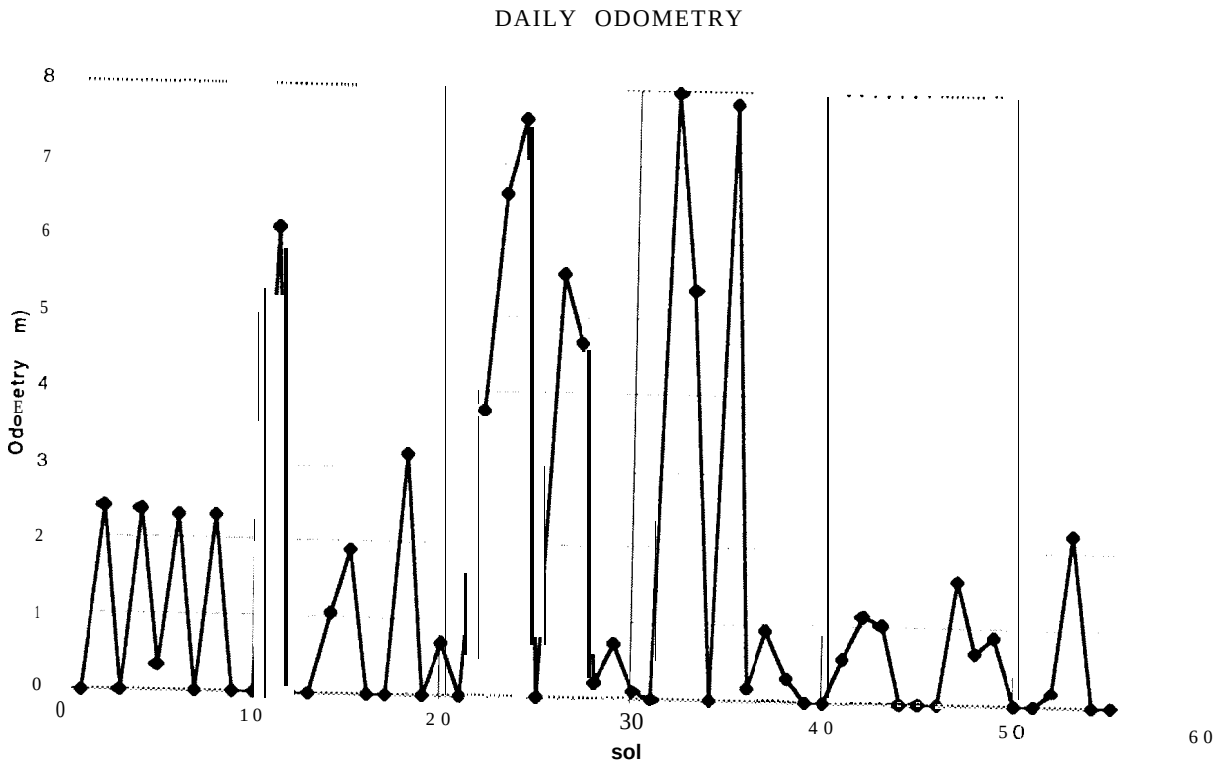

Figure 5. Rover Odometry per Sol

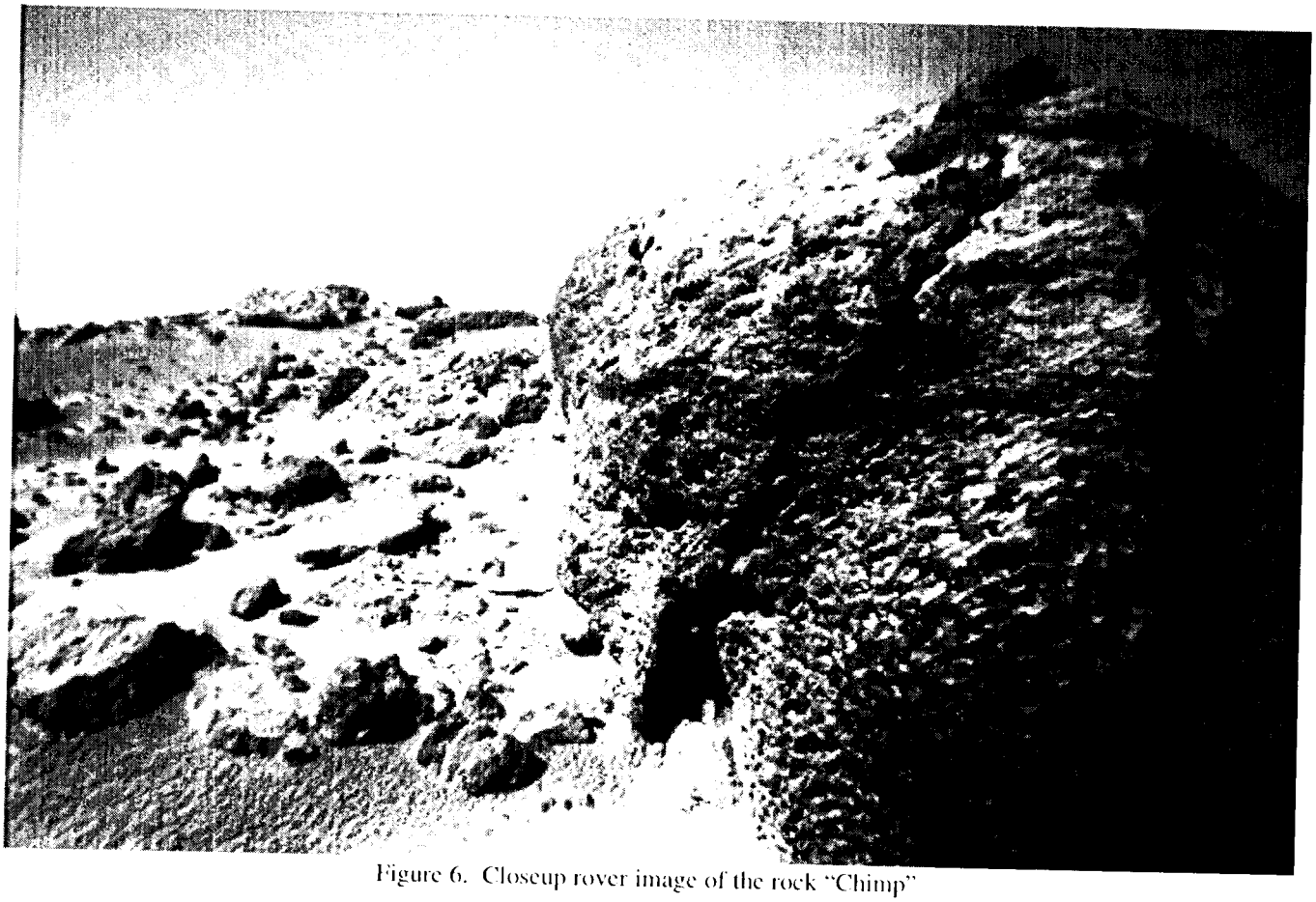

Figure 6. Closeup rover image of the rock "Chimp"

Figure 7. Sand dunes behind the "Rock Garden" visible only from the rover

Figure 8. Initial rover traverse and smooth terrain near lander

Our overall expel-icncc with rover navigation was that while the dead reckoning performance was poor, hazard detection and avoidance worked wel i. Consistent with earl ier ground testing, position error was ro ughly 5- 10% of distance traveled, and average drill of the heading reference subsystem was approximately 13 deg ree s/sol of traverse. The result of this dead reckoning performance was that when autonomous traverse was enabled, the "GO to Waypoint" commands did not always lead the rover to the expected location, hilt the rover nevertheless successfully avoided non-traversable

hazards. In one instance, the rover "threaded the needle" between two hazards which were barely more than a rover width apart. This led the rover into a region near the rock Wedge (Figure 9). Subsequent attempts to use low-level "Move" and "Turn" commands to exit the region required several sols to finally move away from Wedge and into the vicinity of the aptly-named "Rock Garden." (Low-level commands near Wedge often resulted in abbreviated traverses due to tilt or articulation hazard conditions triggered when the rover rode up onto nearby rocks. Misregistration of as little as 10 centimeters of the stereo-derived terrain database and the end-of-day images of the rover contributed to the problem of encountering rather than avoiding obstacles.)

Further complicating traverse operations was the occasional spurious measurements obtained from of two out of three onboard accelerometers used to determine the vehicle's orientation. On some sols these accelerometers would intermittently generate spurious values in error by tens of degrees. (This behavior of the accelerometers had not been observed prior to landing, either (m the flight rover or the groundtest unit.) While the rover's sensor **polling** software routinely filtered out single false values, these erroneous readings sometimes persisted long enough to trigger a tilt hazard and bring the sol's traverse to a halt. The accelerometers could be disabled to prevent unwarranted responses to nonexistent hazards; but this meant that the rover would be unlikely to recognize a true tilt threat if it arose. In some cases, we have needed to disable the accelerometers under exactly the terrain conditions when they would be most useful. Selecting the appropriate state for the accelerometers became part of the planning process of each rover traverse.

Despite some difficulties in operating the rover, Sojourner demonstrated its ability to drive in the terrain of the landing site. Rover "movies" were regularly constructed by capturing a series of images using the lander camera pointed where the rover was expected to drive at a particular time of day. An excerpt from one of these movies is shown in Figure 10, clearly indicating the rover's capability to negotiate a rock nearly a wheel diameter in height.

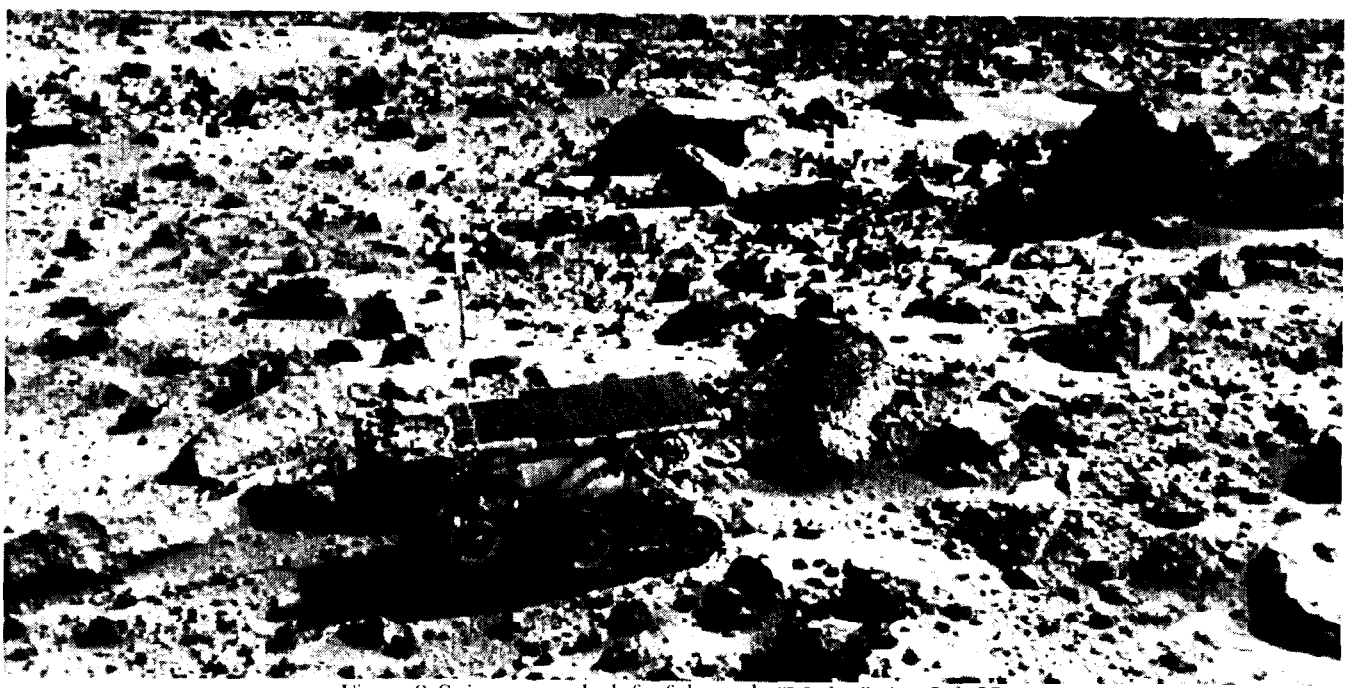

Figure 9. Sojourner to the left of the rock "Wedge" (m Sol 35.
Part of the "Rock Garden" is visible in the upper right of the image.

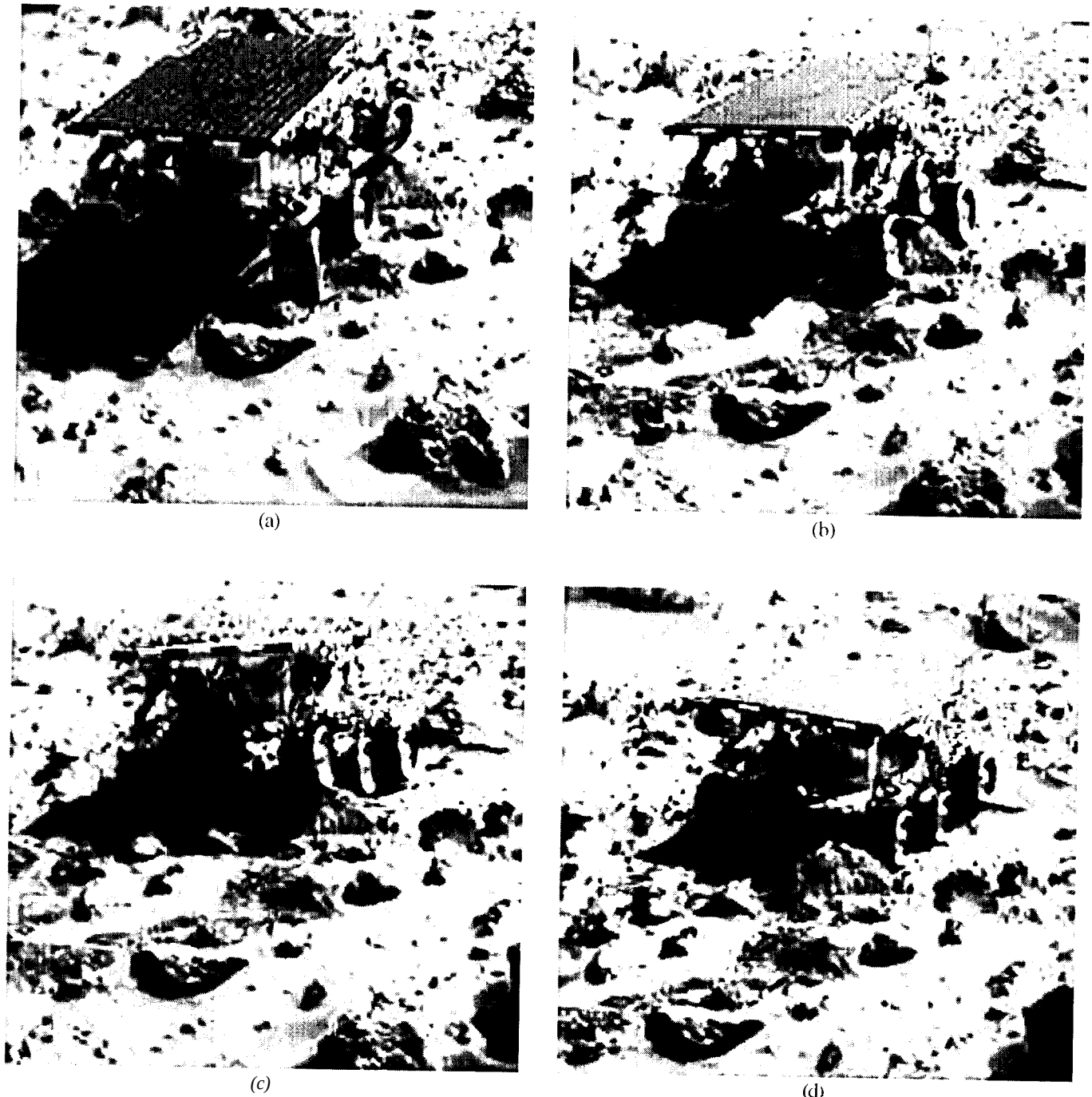

Figure I (). Rover traverse over rock on Sol 24

8. CONCLUSIONS

Unlike spacecraft developed for previous planetary exploration missions, Sojourner operates in a non-deterministic environment, in which tack step may yield unexpected results due 1 0 unk nown terrain condition s. Although modest in capability and complexity, t h e microrover is unique among robotic missions to date in its ability to operate in an unmodeled environment and choose actions based on sensor input to accomplish req uested objectives. As such, Sojourner is probably the most autonon ous deep space probe yet launched.

The autonomous navigation capabilities o f the Sojourner rover have proven sufficient to reach the silts of inter-cst at the Pathfinder landing site. Traverses in the smoother areas within the site has been straightfor wind; navigation through the rockier areas, most notably the region dubbed the "Rock Garden," has been more problemmatic, requiring several sols to cover a few meters of obstacle-strewn terrain. While some of the observed di fficulties are clearly due t o limitations in the implementation of autonomous navigation onboard the vehicle, much can be attributed to the caution of the rover team in enabling the rover's full

suite of hazard avoidance features during specific traverses. This caution is understandable, given that each rover traverse inherently puts the vehicle at risk, and the consequence of a poorly commanded traverse may be the premature end of the mission.

Future planned rover missions, such as the Mars Surveyor Program 2001 mission, will not have the luxury of accomplishing their objectives w'bile maintaining such a conservative approach to risk. In these missions, the rover will be required to traverse approximately 100" meters per sol in order to reach sites of scientific interest and collect samples for eventual return to Earth. This is equivalent to performing all of the traverses of the Sojourner rover during the entire Pathfinder surface mission to date in a single sol. W'bile such long distance traverses will clearly entail a significant increase in required autonomous capability for future rovers, Sojourner has already proven the feasibility and value of mobile robots for planetary surface exploration.

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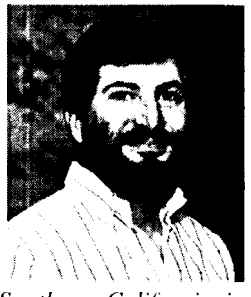
Andrew Mishkin *is the Pathfinder Microrover Mission Operations Engineer, responsible for building the rover operations team, interacting with Pathfinder scientists regarding rover planning, and designing rover command sequences. He graduated from UCLA in Los Angeles, California with a BS and MS in systems engineering. He is a Group Leader for the Robotic Vehicles group at the Jet Propulsion Laboratory, where he has coordinated the development and integration of several planetary rover efforts since 1985. He is currently system engineer for the Mars Surveyor Program 2001 rover mission, and was system engineer for the Control and Navigation subsystem for the Sojourner rover. In his spare time he enjoys hiking, writing, and sculpting in bronze, neon, and steel.*

Jack Morrison *was the primary software designer for the Sojourner rover. During Pathfinder mission operations, he has been one of two primary rover drivers designating vehicle traverses. He is a native of Southern California, with a 1978 BS in Math from UCLA. His career has taken him on adventures in aerospace and commercial development, from air defense systems to video effects boxes; from 8-bit microcontrollers to gigabyte supercomputers; from air force bases to investment firms, and from Venus to Mars. His articles have been published in computer graphics books and his photo with a Cabbage Patch doll published on the Web. His hobbies include virtual air combat and literal equestrian jumping.*

Tam Nguyen *is a software engineer for the Robotic Vehicles Group at the Jet Propulsion Laboratory. Currently, he is a software engineer for the Microrover of the Mars Pathfinder Project and also a member of the Mars Pathfinder Microrover Downlink Data Analysis team. Since 1988, he has developed software and integrated hardware in the areas of motion control and navigation for several planetary rover research programs. Prior to these programs, he was a key software engineer for the Three Axis Levitator Project, a physics flight experiment flown on the*

Shuttle. Nguyen has a BS in Physics and Chemistry and a MSEE from CSU Long Beach, California.

Henry Stone *received his BSEE, MSEE, and PhD from Carnegie Mellon University, in Pittsburgh, Pennsylvania, in 1981, 1983, and 1986, respectively. His dissertation involved the kinematic modeling, identification, and control of robotics manipulators. He joined the Jet Propulsion Laboratory, Pasadena, Ca, in 1986 and initially worked on the Telerobotics Testbed Project which was aimed at developing technologies for controlling multiple manipulators for in-flight servicing of Earth-orbiting spacecraft/satellites. In 1991 he began working in the area of mobile robots and became the Cognizant Engineer of the Hazbot Vehicle, a terrestrial robot designed to remotely investigate and cleanup hazardous material spills. In 1993 he became the Technical Manager of the Mars Pathfinder Microrover's Control and Navigation Subsystem. He has recently been selected to lead the design of the Control and Navigation Subsystem for the 2001 Rover (i.e., the long range rover which will fly to Mars aboard NASA's 2001 Mars Mission).*



Brian Cooper *was the principal developer of the Rover Control Workstation for the MFEX rover, as well as one of the primary rover drivers during surface operations. He graduated from the University of California, Irvine with a BS in Electrical Engineering in 1981, and earned an MS in Computer Engineering from the University of Southern California in 1985. He served as an officer in the United States Air Force from 1981-1985, stationed at Los Angeles Air Force Station (now LA Air Force Base), El Segundo, CA where he worked on military satellite systems. He joined JPL on July 5, 1985 as an engineer working on robotic vehicle research, in the area of computer-aided remote driving. He developed the user interface and control station for numerous robotic vehicles, leading up to this assignment on Mars Pathfinder. Brian's major hobbies include flying, scuba diving, magic (he's been a member of the Magic Castle in Hollywood, CA for over 20 years), and (most important) building his own airplane.*