THE PATHFINDER MISSION TO MARS

Autonomous Navigation and the *Sojourner* Microrover

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TECH VIEW

The Mars exploration program has as an overarching theme the search for and understanding of life, climate, and resources on this fascinating planet. The ability to move about the surface of Mars is key to making measurements and the gathering of the data that address this theme (*1*). In October 1992, the NASA Office of Space Access and Technology funded an experiment to demonstrate the mobile vehicle technologies needed for a Mars surface mission (*2*). That experiment, the Microrover Flight Experiment (MFEX) or "*Sojourner*," flew on the Mars Pathfinder (MPF) mission, which began on 4 July 1997 and ended 26 September 1997.

During the 83 sols (1 sol = 1 martian day = 24.6 hours) of the Mars Pathfinder mission, the MFEX rover was released from the Mars Pathfinder lander and performed its mission to conduct technology experiments such as determining the interaction between martian soil and the rover wheels; navigating, traversing, and avoiding hazards; and gathering data on the engineering capability of the vehicle (thermal control, power generation performance, communication, and so forth). In addition, the rover carried an alpha proton x-ray spectrometer (APXS), which allowed researchers to determine the composition of soil and rock. Lastly, images of the lander taken by the rover were particularly helpful in assessing status of the mission and damage to components.

The MFEX rover (Fig. 1) activities were directed by an operations team on Earth. This team, working under the constraints of limited lander power and restricted antenna coverage at Earth, could (once per sol) command the rover to drive, take pictures, perform experiments, and collect and transmit data to the lander. The rover was required to carry out these tasks safely without intervention from the operations team until the next command opportunity on the next sol. In so doing, the rover used techniques for autonomous control that were (among several technologies) first demonstrated in flight on this mission. One such technique for autonomous navigation and hazard avoidance is briefly described below (*3, 4, 5*).

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The "Go to Waypoint" command was the primary implementation of autonomous navigation on the MFEX rover. This command was issued by the member of the operations team called the "rover driver." The driver used rover camera images, lander stereo camera images taken of the rover in the terrain, and portions of a stereo terrain panorama to identify the rover location and the site of interest (the goal location of the "Go to Waypoint" command). Through a graphic overlay system used with the stereo images, the driver specified the *x* and *y* coordinates of the rover location and the new target. These coordinates were in a coordinate frame (the "surface-fixed frame") that became fixed to the surface of Mars at the time the MPF lander completed sun-finding and identified the direction of martian north on sol 1. Intermediate waypoints (as needed) were also defined by the driver if there was a preferential path toward the final destination (such as a route to avoid obvious hazards along the path). If the rover was not already facing the next waypoint, it was commanded to turn toward the goal, until it faced the destination. These commands ("Go to Waypoint," turns, and a command to update the position of the rover in the *x* and *y* coordinate frame) were sent to the rover as part of a single command sequence.

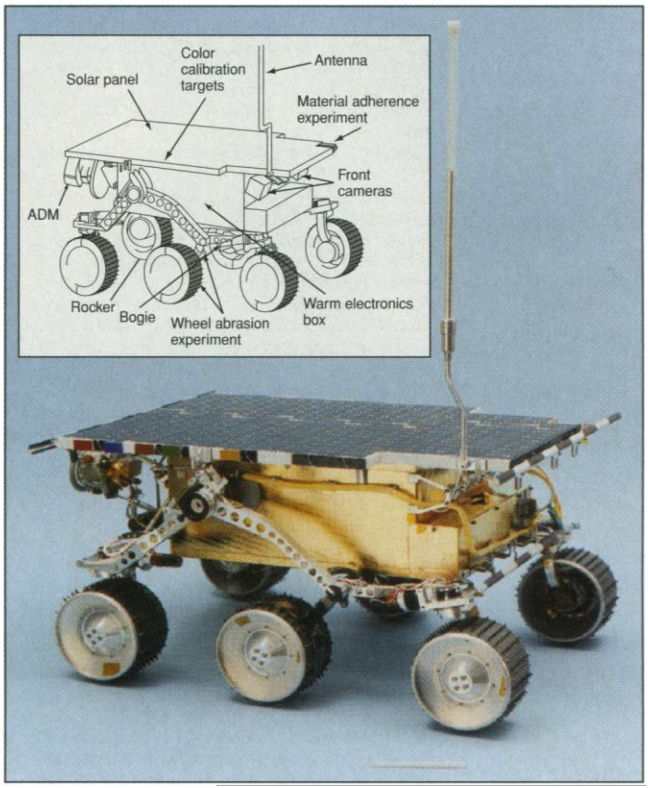

Fig. 1. The MFEX rover. Inset shows key components.

Upon execution of the "Go to Waypoint" command, the rover drove an approximate straight line, adjusting its path when it detected drift off its course or encountered a hazard condition. During execution of a "Go to Waypoint" command, the rover updated its position relative to the lander to determine (at a minimum) if it had reached the objective of the traverse. This position relative to the lander was kept in the same *x* and *y* coordinate system as the commands developed by the rover driver back on Earth. The update to position was performed by a form of dead reckoning. Encoder counts were accumulated on each of the wheel actuators, where a single encoder count was registered each time the motor shaft of the actuator completed a revolution. The accumulated counts on each of the six wheels were averaged to determine the number of motor revolutions executed. Given the gearing ratio of 2000:1, encoder counts were turned into wheel revolutions and thus distance traveled. During turns, the rover measured the change in orientation by integrating the output from an onboard rate gyro. Distance and angle were then used to compute an *x* and *y* location.

The rover could autonomously identify several types of hazards. Among these were proximity-detected rocks, drop-offs, slopes, excessive tilt of the vehicle, a triggered contact sensor, or a combination thereof. If the rover detected a proximity hazard, the vehicle turned in place in increments, until the hazard was no longer detectable. Then the vehicle drove forward one-half vehicle length, after which it resumed normal traverse operations, heading back toward the goal location. At this point, the rover maintained no memory of the hazard that it had just avoided.

Proximity hazard detection was performed with the forward cameras and five laser stripers.

Every 7 cm of traverse, the rover stopped and executed a sensing cycle. The rover captured an image both with and without a laser active. Selected scan lines from each image were differenced to locate the laser spot in the scene. (Figure 2 shows the infrared laser stripe, as seen by the rover during surface operations.) If the terrain is flat and level, as referenced from the rover, the laser spot was visible in a known position along the scan line. Deviations from flat and level ground would cause the laser spot to slide along the scan line, indicating a rock or depression. If the spot could not be found in the difference image, a significant drop-off may exist. Repeating this process for five lasers and four sets of scan lines per difference image generated a set of 20 terrain height measurements. Height differences between adjacent measurements could indicate a rock or hole; sufficient height difference between the lowest and highest measurements in the set indicated a steep slope or drop-off. False hazard detections could occur if the camera view of a laser spot was blocked by a craggy surface; so ignoring a small number of data drop-outs was possible by modifying parameter settings in appropriate terrains. During operations on Mars, the rover was commonly directed to accept up to three data drop-outs before avoiding the drop-outs as a hazard.

The geometry of the laser stripes was arranged so that obstacles could be detected to the sides of the rover traverse direction at sufficient range so that the entire rover's turning circle (a circle 70 cm in diameter) was free of hazards. This allowed the rover to turn around in place and drive forward to avoid an obstacle. If the density of hazards in the terrain was too high to permit the vehicle to maintain a clear turning circle, a "thread the needle" approach could be enabled. This technique permitted the rover to drive between obstacles that were apart at least one vehicle's width. If enabled, the rover would attempt to drive in a straight line along the perpendicular bisector between the two obstacles. It would continue driving until it found a clearing large enough to turn around in before a specified distance was elapsed. If no such clearing was detected, it backed straight out to the point at which the "thread the needle" was initiated. Another direction for driving would then be attempted.

Fig. 2. Image of laser stripe used as navigational guide from front left rover camera.

Excessive tilts were measured with onboard accelerometers (one aligned to each axis of the vehicle). These accelerometers served as a set of inclinometers, measuring the angle to the local gravity vector. An angle measurement beyond a threshold (not greater than a 30° slope) represented an excessive slope condition. When this was encountered, the rover would turn away from the excessive slope, traverse beyond the hazard, then turn back in the direction of its destination.

Contact sensors provided the hazard detection system of last resort for the rover. Sensors were 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 were incorporated into the APXS deployment mechanism (ADM), located at the rear of the rover. If an obstacle in the rover's path was not detected by the proximity hazard detection system, the triggering of any of the bumper contact sensors would either abort the traverse or cause the rover to back up, turn, and avoid the hazard.

If a specified waypoint destination was not reached within the time allotted for the execution of the command, the traverse would end and an error "flag" was set in the onboard command execution software. This error flag prevented the rover from continuing unproductive attempts to achieve an unreachable goal. Depending on the parameter settings in the sequence, any remaining traverse commands were skipped (because the rover was not where it was expected) or the rover continued on to the next specified location.

The autonomous navigation performance of the rover on Mars generally equaled or exceeded the performance observed during tests on Earth. Because of the nearly obstacle-free nature of the terrain in the immediate vicinity of the lander, initial rover traverses were commanded through low-level moves, with no "Go to Waypoint" commands used. By sol 12, once the laser/camera hazard detection system was calibrated (an example of a measurement is shown in Fig. 2), the first "Go to Waypoint" command was executed. Consistent with earlier ground testing, position error was roughly 5 to 10% of distance traveled. (The average rover traverse during the mission was about 2 to 3 m/sol.)

The average drift of the heading reference subsystem was approximately 13° per sol of traverse. The result of this dead reckoning performance was that autonomous traverses through the "Go to Waypoint" commands did not always lead the rover to the expected location. However, the hazard detection system worked well, successfully keeping the vehicle away from nontraversable hazards.

Although some of the observed difficulties were clearly due to limitations in the implementation of autonomous navigation onboard the vehicle, the performance can also be attributed to the caution of the operation team in enabling the rover's full suite of hazard avoidance features during specific traverses. This caution was understandable, given that each rover traverse inherently put the vehicle at risk of a premature end of the mission.

In future planned rover missions, such as the Mars Surveyor Program 2001 mission, the operations team will not be able to meet the mission objectives while maintaining a cautious approach to autonomous navigation. In these missions, the rover will be required to traverse approximately 100 m/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 MFEX rover during the entire Pathfinder surface mission in a single sol. Such long-distance traverses will require a significant increase in autonomous capability. Under consideration for this future mission are onboard techniques for terrain feature tracking, creation of obstacle maps, and visual tracking to targets that may aid mission performance through improvements in autonomous navigation.

References and Notes

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6. This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

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