JPL ROVER TECHNOLOGY PROGRAM

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ABSTRACT

The National Aeronautics and Space Administration (NASA) has embarked on a new mission concept for its planetary program. This new mission concept calls for smaller, lower mass, cheaper systems, The Mars Pathfinder micro rover mission scheduled for launch in 1996 embodies this new mission concept, The Pathfinder, however, will have limited capabilities. It will only traverse tens of meters in the vicinity of the lander vehicle, It will have no manipulation or sampling capability, and very limited flight instrument placement ability. The system is designed to navigate fairly benign terrain and will have minimal onboard hazard identification. The new NASA Mars Rover Technology Program is a focused research program which will provide the enabling technology for a later, more robust science and sample return mission to Mars, or other planets like Venus, This paper describes the current and future Mars Rover Technology Program and provides a description of the micro rover system. Examples of some of the recent performance testing, to explore limitations of system capabilities and systematically improve navigation robustness, are presented,

INTRODUCTION

The Mars Rover Technology Program is designed to enable science and sampling capabilities beyond the Mars Pathfinder micro rover which is scheduled for launch in 1996. Although the JPL NASA rover development effort has been in existence for several years, it has not looked in detail at performance metrics, design benchmarking, and in-depth mission scenarios for which a rover was specifically constructed. The intent of the technology program is to rigorously evaluate and test existing micro rover technologies and capabilities in the context of flight-like constraints such as performance (e.g., navigation on Mars-like terrain such as

Viking I and 11, or, completing a specific mission scenario from beginning to end), cost (e.g., mass, power), and risk (e.g., reliability, mission completion). Once the limitations of existing technology are understood, the ultimate goal is to develop and test needed new technologies in the same context, This technology program has been carefully designed with the theme of "faster, better, cheaper. " By not arbitrarily assuming existing technology may not meet the needs of an out-year Mars sample return mission, the program retains useful, already proven technology, thus saving the real investment in time and dollar resources for the serious technology gap areas. The foundation on which the technology program has been built is described in greater detail in the next section.

ROVER TECHNOLOGY PROGRAM FOUNDATION

The rover technology team developed an initial foundation for identifying technology thrusts by talking to several members of the science and Mars mission planning communities (Refs 1, 2, 3, 4, 5). Additionally, the team reviewed previous rover mission plans from the Mars Rover Sample Return (MRSR) program, and Viking data (Refs 6, 7, 8, 9, 10). 'l'he net result of this analysis revealed the following essential information. First, the mission profile data indicated that with the current direct entry approach planned for Pathfinder, the subsequent landing uncertainty envelope will be on the order of an ellipse 50 by 150 km. By going into orbit first with gradual entry, the error envelope can be reduced to 10's of km's, This data is important for two reasons: 1) it means that the sizable landing uncertainty envelope will require a conservative mission approach for touchdown, leaning more towards landing in benign open areas that may not be as geophysically interesting as desired, and 2) given that the landing uncertainty, in the best case, will still probably be on the order of 10's of km's, some type of mobile rover system seems reasonable, and that system will need to be capable of navigating sizable distances.

Second, given the projected landing uncertainty and subsequent conservative touchdown approach, it appears that the most interesting geophysical and geochemical sites will most likely not be in the immediate area of the lander. This is not an absolute, but the longer range mobility option offers considerable flexibility in exploring science acquisition options once on the planet surface.

Third, and somewhat related to the conservative landing approach, because of the failure of the Mars Observer system (confirmed December 1993), the mission community is left only with the Mars Viking Orbiter image data as a planning base. Unfortunately, the resolution of the Viking images is only on the order of 100 m's per pixel. This means that a seemingly benign landing site could, indeed, be full of large boulders or be a fault zone. Given this possibility, it appears important to build a rover system which can negotiate a large variety of terrain or hazards, and recover from non-catastrophic error or fault conditions.

Fourth, current mission planning scenarios for uplinking commands and downloading telemetry data show that a combination of limited lander power and duty cycle for driving the transmitters, coupled with user schedule conflicts for the Deep Space Network (DSN), will most likely reduce the allowable 13arth-to-lander-to-rover communication frequency to once per day, This means that the system will need to operate largely in an autonomous mode most of the time.

Fifth, the science community, given greater options for reaching areas of scientific interest, is showing interest in developing a significant technology base for reliably deploying and pointing sensors and science instruments (both above and below the surface), as well as acquiring samples and returning them to the lander for in-situ analysis. The need to return to the lander after long sorties is driven by the fact that the micro rover will not have the on-board real estate to enable sample analysis, whereas the lander will; and, the fact that the rate of advancement in micro-miniaturization of instruments does not appear to be progressing at a speed to enable the rover to carry a complete sensor/instrument array on board. In total, existing mission data strongly suggests that whatever mobile deployment vehicle is employed, it will most likely have to travel sizable distances autonomously (on the order of at least 10's of km's), navigate a variety of terrain types and maintain an accurate heading, avoid hazards and recover from fault conditions. In addition, it must be outfitted to perform a significant array of instrument deployment and sampling tasks, and be able to return accurately to the landing vehicle.

ROVER TECHNOLOGY THRUSTS

in order to move the overall system capability and supporting technology base in the direction of 1 km^{-1} traverses, the team identified several hurdles which, when resolved, will provide the technology foundation to meet the above desired mission goals. Those hurdles are as follows: 1) Where is the science site relative to the lander?, 2) Where is the rover now?, 3) Where are the hazards relative to the rover?, 4) How does the rover get to where it wants to go (i e., the science site)?, 5) How does the rover perform the science task once at the site?, and, 6) Are things proceeding acceptably; and, how does the system recover when things go wrong?

1. Near Term Technology Thrusts (FY94)

The team recognized that not all the technology development required to clear these hurdles could be accomplished at one time. Therefore, a phased development approach was taken.

Following the above philosophy of evaluating existing technology, one of the primary near term technology thrusts is to assess the performance of the existing micro rover system and refine the navigation and control algorithms to make the system as robust as possible. In the near term, this includes algorithms for handling sinkage and slippage and hazard avoidance, This performance assessment addresses all aspects of navigation such as on-board sensing and perception, vehicle drive mobility and stability, and available computing. Sensitivity to mass and power constraints is also an important consideration in introducing new technologies in the gap areas revealed by the evaluation. The assessment then sets a firm foundation for knowing where to invest in advanced navigation technology from both a research and implementation standpoint. The vehicle performance evaluation is stated here first because it impacts several of the hurdles, namely, 2, 3, 4, and 6, with particular emphasis on how the rover gets to where it wants to go (hurdle 4). A separate rover benchmarking activity which will evaluate different types of rovers (e.g., wheeled vs. legged) is also being initiated early as an adjunct to the performance evaluation.

The first two hurdles, where is the science site and where is the rover, are related because ultimately either the lander or rover are going to have to establish the correct relative heading to reach the science site. For the near term, gross Viking Orbiter landmarks and lander touchdown position will be used at the Earth ground based operator workstation to establish the initial rover heading. An expansion of the ground-based operator workstation will utilize lander stereo imaging, terrain maps, stochastic projection of mission success likelihood, and human designation of way points using a graphic icon overlay. This near term capability will enable rover path planning. Within the immediate vicinity of the lander, rover dead-reckoning and lander stereo imaging will be implemented to locate the rover accurately and allow it to return to the lander. Recognizing that improved deadreckoning and global positioning will be required for kilometer scale traverses, the team decided to set a foundation for out year research by initiating early-on a study and evaluation of advanced over-the-horizon sensors (e.g., sun, beacons).

Hurdle number three, where are the hazards, not only addresses the issue of avoiding vehicle snags or untraversable terrain (e.g., sheer dropoffs/inclines), but also highlights the need to identify landmarks and goals. For the near term, the team decided to explore the option of using a low-energy laser ranging system for the initial imaging goal/hazard identification work. Research in non-geometric hazard detection will also be done using contact and vehicle state sensors (e.g., sinkage, slippage). To accommodate the potential increase in computational loading resulting from the on-board image processing, a temporary commercial processor will be integrated to not only allow greater computing power, but also help define out-year computational requirements.

The fifth hurdle, how will science be performed, addresses the issue of how to build a manipulation system which will be able to perform the array of expected science instrument sensor placement and sampling tasks once the site is reached. For this year, the approach being taken is to develop a reasonably complete set of functional requirements, followed by an intensive design, graphical prototyping, and component modeling/testing phase. The actual sampling device will be built and integrated in 1995.

The last hurdle, how to recover when things go wrong, is a very complex issue related to both hazard management and component failures on-board the rover. For this year, the team decided to concentrate on the earlier described performance testing to identify and quantify critical failure areas, along with the hazard detection and avoidance research, as a first step. Knowledge obtained from the performance evaluation will highlight the out year research targets. Additionally, as an adjunct to the performance testing, the research in rover fault recovery at MIT is also being leveraged.

Reference was made to leveraging other parallel research activities in the above discussion. The Rover Technology Program has several support contracts planned for the near term. MIT is under contract to perform research in the areas of real-time hazard avoidance, fault management, and micro-miniature end effecter/tool development. Martin Marrieta Corp. (MMC) has been contracted to design and develop sensor suites for over-the-horizon navigation. McDonnell Douglas Corp. is supporting research in the area of virtual reality science acquisition systems for integration into the ground based operator workstation. Finally, the University of Southern California (USC) has been tasked to perform the rover benchmarking studies.

In closing this subsection, it is important to recognize that, although it is not the intent of the rover technology program to augment the existing Pathfinder micro rover effort, the FY94 research areas related to making the navigation and control algorithms more robust (e.g., management of sinkage and slippage), rover based goal identification, near lander rover position estimation, and the expanded operator workstation capabilities, represent delta improvements in Pathfinder capability. If appropriate, these technology components will be made available to the Pathfinder flight project.

2. Far Term Technology Thrusts (FY95 through FY97)

The post FY94 research activities are not defined in detail at this time since the project has just gotten underway. However, in line with the above projected mission and performance scenarios outlined in the foundation, several research areas have been identified. Perhaps the greatest priority will be to develop the over-the-horizon sensor suite to enable the rover position and heading to be accurately determined. Since it is unknown at this time whether an orbiter based global positioning system will be available, it will be assumed that the global positioning system will have to be surface based (e. g., use of sun sensors or beacons). Another activity directly related to over-the-horiz,on navigation is the generation and use of maps on-board rover. While the operator will be initially generating the maps or way points, once the rover is beyond the vision of the lander it will have to rely on its own deadreckoning and global sensing to maintain its heading. In terms of local navigation through rock fields or gullies where major landmarks are not available and global sensing may be intermittent, it may have to generate an internal map of hazards or way points in case it must retrace its path back to a known major landmark or communication zone. What constitutes a map and how on-board maps are generated represents yet another out year research thrust.

One obvious priority will be the construction, integration, and testing of the on-board science instrument deployment and sampling device, as addressed earlier for the FY95 timeframe. This activity will also include development of necessary end effecting and/or tooling.

Another priority will be the need to use machine vision to identify interesting science targets or perform on-board matching of simple internal landmark models with terrain landmarks as a navigational aid, and backup in the event of a heading sensor failure. The foundation set in 1994 towards determining the upper bound on the computational loading relative to the big drivers such as vision processing and hazard/fault management heuristics, will allow the team to establish requirements for the next generation on-board computing pl at form and build the computing system. This step will allow the technology program to move more quickly into the area of autonomous error/fault recovery and non-geometric hazard detection/avoidance, which are also major technology thrusts.

Although the goal is to move as much intelligence on-board the rover as possible, it is understood that computational and power constraints will not make it reasonable to perform all sequencing and problem diagnostics on-board. Therefore, another out year thrust will be to enhance the operator ground workstation to include virtual reality mission planning tools, high fidelity rover simulations, task and resource sequencing, and diagnostics.

Finally, the rover benchmarking activity is recognized as a very complex problem. New vehicle designs will be generated over the next several years and will require careful examination and testing. Therefore, the benchmarking activity will be a continuing research effort for the duration of the technology program. The results of vehicle testing and comparison will be published on a periodic basis.

ROVER TEST PLATFORM ENVIRONMENT

The most important component in the test environment is the Rocky 3,2 micro rover. This version of the micro rover is nearly a duplicate of the Pathfinder Rocky 4.2 platform in terms of size and component equivalence. The micro rover is approximately 61 cm long, 45.7cm wide, and 40.6cm high, The vehicle chassis is articulated to enable the rover to climb over obstacles. Currently the vehicle can navigate obstacles which are 1.5 wheel diameters high. Each wheel has its own independent drive motor; with the ability to program each motor to drive at a different velocity if needed. Although the current software environment for Rocky 3.2 is the same as Rocky 4.2, it will diverge as the research program progresses. As stated above in the technology program description, there are potential opportunities for some convergence if some of the software technology is transferred to the flight program. The present on-board computational platform is the 80C85 microprocessor with 288 Kbytes of bank-switched RAM/ROM. Dual CCD cameras (768x484 pixels) and 5 laser stripe projectors make-up the on-board perception system. Navigation control for is done using odometer encoders on all the wheels, pots on the chassis and steering, three (3) accelerometers, and a quartz rate gyro. Commands generated at the operator workstation are forwarded to the lander, where they are then relayed to the rover via radio link, The overall micro rover assembly is shown in Figure 1.

The rover technology program will develop and test the component and system technologies in two major environments; namely, indoor and outdoor. The indoor environment will be where the research and controlled testing (i. e., lighting, terrain type, hazard type, calibrated landmarks and traverse paths) will be performed.

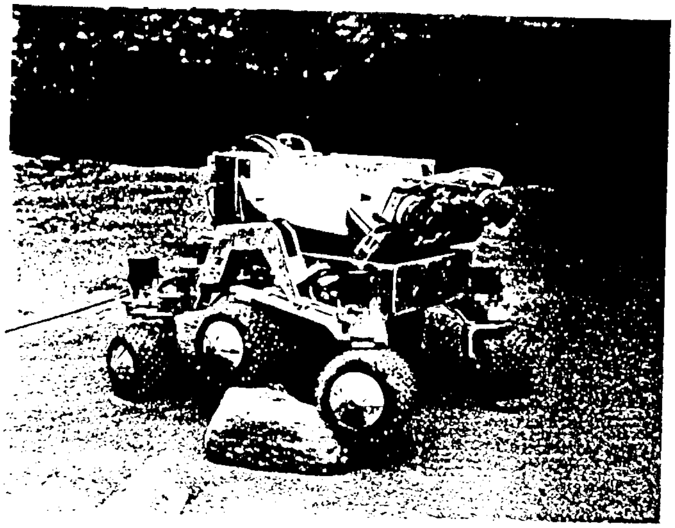

Figure 1. Rocky 3,2 Microrover Test Platform

Figure 2. Microrover in Large Indoor Terrain Simulator

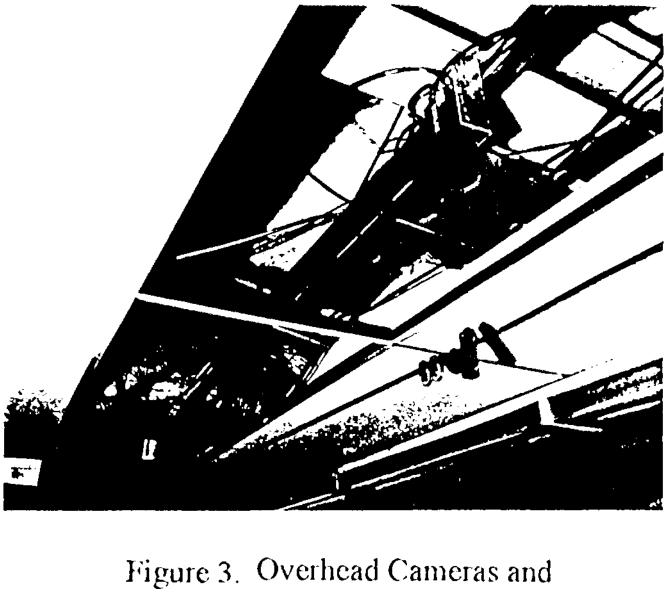

Figure 3. Overhead Cameras and Support Structure for Metrology System

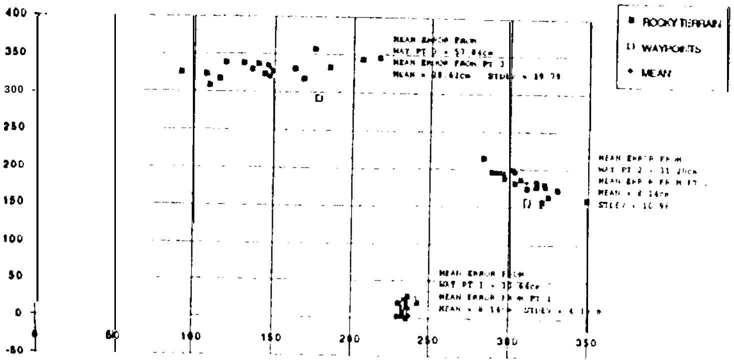

Figure 4. Plot of Cumulative Rover Heading Error in X-Y Plane (Cm)

To facilitate these activities a large terrain simulator has been constructed with several different features. For example, initially, extended testing of cumulative heading error will be conducted in the simulator free of rocks, obstacles, or hazards. A Viking I type mildly cluttered rock terrain (Ref 11) will then be installed along with artificial hazards (e.g., slip environment, sinkage environment using fine powder, a trench of varying depth and width, rock rings) (see Figure 2) Last, a Viking 11 cluttered rock terrain (Ref 11) will be installed to test vehicle performance in rough terrain.

A camera metrology system has been mounted overhead to track the rover to an accuracy of roughly 1 cm in the horizontal terrain plane. The metrology system has four (4) cameras mounted in a rigid structure such that each camera field of view overlaps about two vehicle lengths (i. e., 1.2m). This way, the system insures tracking the vehicle from one camera field of view to the next, The four cameras provide almost full coverage of the terrain simulator (see Figure 3). The overhead tracking camera images and sensor data will be sent back to a VME chassis, and then to the Silicon Graphics Inc. (SGI) operator workstation for reduction and analysis.

Another important component of the test environment is the lander mockup. The current lander design was developed to resemble the proposed multi-probe carrier vehicle concepts being considered by the Pathfinder project. However, since this technology program is focused on rovers, it was not necessary to exactly duplicate any particular lander design. The lander mockup will be shaped like an equilateral triangle (1 .34m on an edge), at the base. Hinged trapezoidal petals (1 .34m on the base hinged edge, .54m at the top edge, and .9m high) are held in place by magnets in the closed, stowed configuration; and, fold down to allow rover egress at run-time. The rover sits inside the lander on the base and is held in place with wheel clips, A 2 degree of freedom (DOF) pan/tilt camera head is mounted on a smaller equilateral triangle base. The pan/tilt stereo cameras are at a height of 1.2tn above the ground. Stereo images are sent back to a VME chassis with the appropriate camera control boards, framcstorers, and analog to digital conversion/ formatting, for transfer to the SGI workstation over an ethernet link.

The last major component of the test environment is the outdoor test support vehicle. The support vehicle is a standard long-bed van configured to house the SGI workstation, VME chassis, lander mockup with rover, additional electronics cooling, power generator, rover support equipment and tooling, and 200m cable power/communication cabling. The current outdoor test and demonstration location is Avawatz, Baker, California. This site was picked because of its similarity to typical Mars terrain. The operational scenario will be to locate the van in a area approximately 200m from the site, place the lander/rover at the site, and then run the power and communication cabling from the van to the lander.

TEST AND DEMONSTRATION SCENARIOS

1. Indoor Testing Scenarios

The above test environment description provided an overview of the overhead metrology system. Reference was also made to the utilization of on-board sensor data to assist in quantifying the rover performance, A host of tests arc planned for the micro rover in the indoor terrain simulator. Testing has already started on examining cumulative heading errors in both smooth and mildly rocky terrain. Figure 4 provides an example of one series of cumulative heading error tests in which the rover was programmed from the O-O (x,y) position to go to three known way points (known to within +/-1 cm) over a total traverse distance of 5,5 m. The plot shows that the variance increases by a factor of two from one way point to the next. However, at way point 3 the mean error of roughl y 30 cm is still within the range of object identification for the laser rangers (i.e., the laser rangers cover a swath of 1.0m). The mean error is roughly 5 percent of the total distance traveled. The heading error data was gathered over 200m of cumulative trials. Testing of this nature has helped the team fix design flaws, study sensor noise problems, and assess sensor and mobility design robustness and identify alternative higher performance vendor products.

Other kinds of tests will include studies of contact vs. look-ahead sensor performance relative to deadreckoning and hazard avoidance. Controlled tests will be done on slippage and sinkage. Hazard detection/management tests will be conducted to determine the limits of existing sensing and behavioral control algorithms. These tests will also examine when on-board maps should be generated and help define the software algorithms for gathering the data, control options, and determining which control options to execute. The heading error tests in controlled terrain conditions will continue. Performance tests of the on-board laser ranger/CCD camera system will provide the basis for determining the appropriate landmarks and goal identification algorithms, This testing will be implemented using both the rover and lander imaging systems. The operator workstation will also be tested from the standpoint of examining the ability of operators to accurately locate landmarks and generate hazard free paths.

2. Outdoor Test Scenario

The outdoor demonstration scenario is tentatively planned to be run in a desert type environment. The Avawatz, Baker, California site was picked because it contains a reasonable rock distribution and terrain profile similar to that of Viking I Mars terrain. While the indoor testing is focused more on the research aspects of the technology program, the outdoor testing has “engineering for robustness” as its primary goal. Given that once a micro rover system is placed on the surface of Mars it must face an unknown terrain and deal with a harsh environment, the team recognized the need to perform similar tests and demonstrations of robustness in an uncontrolled environment. The FY94 demo has two components, The first part of the demo calls for the rover to egress from the lander and make two to three traverses away from the lander to designated landmarks with return to the lander in vicinity of an instrument pallet, Each traverse will be nominally 30-50m, somewhat resembling a clover leaf. This element of the demo illustrates navigation reliability.

The second part of the demo calls for the rover traverse away from the lander to the same designated landmark nominally three times, with each traverse being on the order of 30-50 m. This element of the demo illustrates system repeatability.

CONCLUSION

The Rover Technology Program has been kicked off with a very aggressive testing and technology development activity. The planned 100m+ demonstration in open desert terrain will represent a strong first step towards the 1 km+ traverses planned for post FY94. Additionally, the technology program is based on a realistic Mars landing and mission scenario.

The derived science and sampling tasks are based on a solid foundation of desired functional capabilities directed by the science community. A science review committee has been formed to insure the technology program maintains a well focused research and development effort. This rover technology program will provide a substantial capability base for future, more extensive, missions to Mars. An aggressive technology commercialization effort is also currently being developed.

ACKNOWLEDGMENTS

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. Weisbin, C., “Rover Technology Program Plan,” Jet Propulsion Laboratory (JPL), July 28, 1993.
2. Personal Communication, Volpe, R. and Zimmerman, W. (Rover Technology Team), with Golombek, M. (MESUR Pathfinder Project Scientist), October-November, 1993.
3. Personal Communication, Zimmerman, W. (Rover Technology Team), with Banerdt, 13. (planetary Geoscience, seismometers), October, 1993.
4. Personal Communication, Volpe, R, (Rover Technology Team), with Knokc, P. (Mars Sample Return), October 1993.
5. Personal Communication, Zimmerman, W. (Rover Technology Team), with Wellman, J. (MESUR Flight Project), October-November 1993.
6. Kieffer, H., et.al., Mars, University of Arizona Press, Tucson and London, Copyright 1992.
7. FMC Corp., “Mars Rover/Sample Return (MRSR) Studies of Rover Mobility and Surface Rendezvous,” Final Report, Contract no. 958074, December 1989.
8. Ezell, E., et.al., On Mars-Exploration of the Red Planet 1958-1978, NASA SP-4212, NASA, 1984.
9. Solomon, S., et.al., “Scientific Rationale and Requirements for a Global Seismic Network on Mars,” LPI Technical Report no. 91-02, 1991.
10. JPL, “Mars Sample Return Mission,” JPL document no’s D-1845 and D-3 114, 1984-1985.
11. Christensen, P., Moore, H., “The Martian Surface Layer,” Mars, pgs. 686-729, 1991.