MARS PATHFINDER MICROROVER - IMPLEMENTING A LOW COST PLANETARY MISSION EXPERIMENT

IAA-L-0510

J. Matijevic
Mars Pathfinder Microrover Manager
Jet Propulsion Laboratory - California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

ABSTRACT

The Mars Pathfinder Microrover Flight Experiment (MFEX) is a NASA Office of Space Access and Technology (OSAT) flight experiment which has been delivered and integrated with the Mars Pathfinder (MPF) lander and spacecraft system. The total cost of the MFEX mission, including all subsystem design and development, test, integration with the MPF lander and operations on Mars has been capped at $25M. At time of delivery, approximately two-thirds of the cost has been incurred. The components of this rover, implemented in combinations of commercial, mil-spec and some space qualified parts, have undergone and passed environment and operational test series derived from that expected in configuration with the lander and in operation on the Martian surface.

This paper discusses the process and the implementation scheme which has resulted in the development of this first Mars rover. The subsystem designs which have proven successful (and not so successful) are also described briefly along with the requirements and constraints (with cost an integral factor) which resulted in these designs. The qualification status of these subsystems is also presented.

INTRODUCTION

On July 4, 1997 the Mars Pathfinder (MPF) spacecraft enters the Martian atmosphere, is braked successively by an aeroshell, parachute, rockets and airbags. Once on the surface the lander (the remaining portion of the spacecraft) rights itself by retracting airbags and deploying petals. On the petals are solar panels which will power the lander for the remainder of its mission. On one of these petals is the Microrover Flight Experiment (MFEX), the first roving vehicle on Mars.

The MFEX is a flight experiment of autonomous mobile vehicle technologies, whose primary mission is to determine microrover performance in the poorly understood planetary terrain of Mars. After landing, the microrover is deployed from the lander and begins a nominal 7 sol (1 sol = 1 Martian day) mission to conduct such technology experiments as determining wheel-soil interactions, navigating, traversing and avoiding hazards, and gathering data which characterizes the engineering capability of the vehicle (thermal control, power generation performance, communication, etc.). In addition, the microrover carries an alpha proton x-ray spectrometer (APXS) which when deployed on rocks and soil will determine element composition. Lastly, to enhance the engineering data return of the MPF mission, the microrover will image the lander to assist in status/damage assessment[4].

DESCRIPTION

The MFEX rover (see Fig. 1) is a 10.5kg, 6-wheeled vehicle 60cm x 48cm x 30cm in size. A rocker bogie design is employed which allows the traverse of obstacles a wheel diameter (13cm) in size. Each wheel has cleats and is independently actuated and geared providing the capability of climbing in soft sand and scrambling over rocks. The front and rear wheels are independently steered, providing the capability for the vehicle to turn in place (74cm turning diameter). The vehicle has a top speed of 0.4m/min.

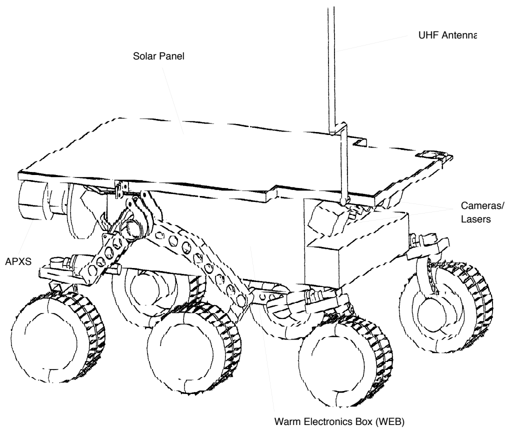

Fig. 1 MFEX microrover

The rover is powered by a 0.22sqm solar panel providing 16W of peak power. The solar panel is backed up by primary batteries, providing up to 150W-hr of energy. The normal driving power requirement for the microrover is 10W.

Rover components not designed to survive ambient Mars temperatures (-110degC during a Martian night) are contained in the warm electronics box (WEB). The WEB is insulated with solid silica aerogel, coated with low emissivity paints, and resistively heated under computer control during the day. This design allows the WEB to maintain components between -40degC and +40degC during a Martian sol.

Control is provided by an integrated set of computing and power distribution electronics. The computer is an 80C85 rated at 100Kips which uses, in a 16Kbyte page swapping fashion, 176Kbytes of PROM and 576Kbytes of RAM. The computer performs I/O to some 90 sensor channels and services such devices as the cameras, modem, motors and experiment electronics.

Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. An average of motor encoder (drive) or potentiometer (steering) readings is used by the computer to determine when to switch off the motors. When motors are off, the computer conducts a proximity and hazard detection function, using its laser striping and camera system to determine the presence of obstacles in its path. The vehicle is steered autonomously to avoid obstacles but continues to achieve the commanded goal location[7]. While the vehicle is stopped, the computer also updates its measurement of distance traveled and heading using the averaged values derived from the motor encoders and an on-board gyro.

Command and telemetry is provided by radio modems on the rover and lander. During the day, the rover regularly requests transmission of any commands sent from earth and stored on the lander. When commands are not available, the rover transmits any telemetry to the lander collected during the last interval between communication sessions. Telemetry received by the lander is stored and forwarded to the Earth.

Communication between the lander and Earth is provided twice each sol for two hours during each period. The command and telemetry functions of the rover are designed to work within these communication constraints[2]. Commands are generally designed at a 'high-level' (for example, 'go_to_waypoint', where a waypoint is a coordinate in the terrain referenced to the location of the lander) and are collected into a sequence for execution by the rover. The sequence is sufficient to carry out the mission functions of the rover on the given sol of issuance.

Commands for the rover are generated and analysis of telemetry is performed at the rover control station, a silicon graphics workstation which is a part of the MPF ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the vehicle in the terrain. Those images, portions of a terrain panorama, and supporting images from the rover cameras are displayed at the control station. The operator is able to designate points in the terrain on these displayed images. These points serve as goal locations for rover traverses[6]. In addition, the operator can use a model of the vehicle which, when overlaid on the image of the vehicle, measures location and heading. This information is transferred into a command file to be sent to the rover on the next sol to correct any navigation errors and command rover traverses.

IMPLEMENTATION APPROACH

The MFEX has been implemented by a small team of engineers (32 at peak staffing) who at the outset planned the development within the constraints of the $25M cost cap[5]. As such, the early focus of the effort was the development of a system design, a baseline of functionality of the vehicle which was used for costing the approach. A few basic functions were recognized as required for the mission:

- on-board navigation and knowledge of location from the lander
- hazard detection and avoidance
- mobility suited for a terrain of sand with many small (under 10cm) rocks and few large (greater than 1m) rocks
- traverse plan developed from images displayed at a ground control workstation

These functions were developed as prototypes in the NASA OSAT rover technology program through the 'Rocky' series of vehicle developments[1].

With the FY92 vehicle (Rocky 4) as a technology baseline, the team developed a cost estimate for the implementation. Several components of the eventual flight vehicle were recognized as technology challenges:

- motors and gears which would operate at -80degC and survive to -110degC
- thermal design (especially the WEB) which would protect sensitive electronics to be maintained within ±40degC range
- cameras which could be produced cheaply and support the hazard detection system
- communication equipment which would operate with a free-ranging rover
- batteries which would backup a solar panel, subject to a variety of shadowing and tilt conditions
- on-board computing which would process the sensors; execute the basic driving, navigation and hazard avoidance functions of the vehicle; and support the command and telemetry requirements.

In addition, the components as well as the integrated vehicle must be shown qualified for the environments of the mission (e.g., launch within the MPF lander, 7 month cruise to Mars, landing on Mars, operation in the Mars environment).

To accomplish this challenge the team adopted a 'rapid prototype' approach to the implementation. Since in many instances flight qualified components were either too expensive or unavailable, commercial or mil-spec standard components were identified and plans to qualify through a test and selection process initiated. This was done for the case of the motors and gearboxes, the cameras, the radio modems and many electronic components for the rover. In cases in which there were no flight qualified models for the development, as for example the thermal design of the WEB, engineering models were developed and evaluation conducted early in the program. Finally, to facilitate software development and electronic component integration, a Rocky vehicle was delivered from the rover technology program at the start of the project and maintained as a testbed throughout the development.

In the following sections examples of this approach are presented.

Actuators

The mobility capability of the MFEX rover is a function of the rocker-bogie and 'all-wheel drive' design. Ten motors are required : one for each of 6 wheels and 4, one for each front and back wheel steering element. Each motor must survive the Mars surface environment, with night-time temperatures reaching -110degC, and operate during early morning conditions, when temperatures are not warmer than -80degC. When surveying the industry for motors which might satisfy these requirements, motors designed for space flight application are nominally brushless with integrated electronics, not suited for operation at these temperatures. Wire routing to move the electronics from the wheel to inside the rover's WEB would be cumbersome (many wires crossing moving components) and be the source of a heat leak. This dictated looking at an alternate technology, brush motors, which is generally available for commercial not space flight applications. After a survey of commercial motor vendors, the Maxon motor was chosen, with its superior torque versus mass performance and a commutation scheme suited for the prevention of arcing, an issue for the 8Torr atmosphere at the Martian surface.

The actuators for the MFEX rover also require a gearing design which transfers many turns of the shaft of the motor into torque to move kilograms of mass. Again the MFEX project turned to the commercial market to procure a gear box for the application. Early development testing of this gear train and motor assembly revealed freeze-up and high breakaway torque required to start the actuator at temperature. MFEX engineers worked closely with Maxon to encapsulate the capacitors to improve the power-use performance at temperature of the motors. In addition, this testing helped MFEX engineers identify and remove greases and friction from the gearbox which were sources of the freeze-up. The result is an actuator which operates at Mars environment, draws less than 1.5W at maximum output, and has shown no degradation after 8km of lifetime tests at temperature.

Modems

The MFEX rover gathers data during its mission and communicates to a lander for 'store and forward' service to the earth. This free ranging characteristic of a planetary rover makes wireless communication essential. However, space flight examples of such relay communications (shuttle-to-TDRSS, probe-to-Galileo) involve high powered (several 100W of radiated power) systems designed for many kilometers of signal relay. The MFEX rover is planned to range from the lander only 10's of meters and in prototype demonstrations was capable of acceptable communication through low power (under 2W) UHF modems. When surveying the industry, no space flight qualified equivalent systems were available and only a few mil-spec radio modems were identified as applicable, but at a prohibitive cost. The MFEX project turned to the commercial market and, in particular, one of the largest commercial manufacturers of wireless communication devices, Motorola, for a device which would satisfy its data transfer needs.

The RNET modem was chosen both for its low power and rugged packaging, most nearly suited for the mission environment. Yet, this radio modem would need to satisfy thermal requirements (operate from -40degC to +40degC in the WEB), operate under radiation conditions (where latch-up will not occur for a LET below 30), and survive a derived dynamic environment associated with a 50g landing load. JPL and Motorola engineers worked together to characterize performance at temperature and under radiation, and adapt the radio modem and its supporting electronics to function under the required conditions.

In early testing, latch-up of the modem would occur at a LET under 25. However, the latch-up was non-destructive: the modem was left in a latch-up state for over 1hr, power cycled, then shown to work properly thereafter. The adaptation of the modem then involved the addition of circuitry and software control to detect and then correct through a power cycle of the device when a latch-up occurs.

Given that the manufacturers rating of the modem was for operation between of -30degC and +45degC, the MFEX project planned to test the modems at lower temperatures and select those which would operate best through the ±40degC temperature range for the WEB. This testing and selection process resulted in devices which worked acceptably (i.e., bit error rates less than 10E-5) throughout the temperature range as determined through communication to an external, reference modem maintained at room temperature. In characterization tests of pairs of modems where temperatures can vary (the condition of the MFEX mission where a modem on the lander will be at a temperature distinct from that of a modem on the rover), performance degraded: bit error rates of greater than 10E-3 were observed. The cause of the problem was frequency drift in the crystal oscillator (and related parts of the circuitry) of the modem at temperatures below -20degC. An external, temperature controlled crystal oscillator is under consideration for replacement of the crystal oscillator packaged with the RNET modem. This replacement would need to occur after the delivery of the MFEX rover to the MPF flight system and be part of a retrofit, prior to launch. Alternately, a heating scheme has been evaluated and shown to improve the performance of the modems. The modem is equipped with a heater which is powered-on whenever the temperature in the WEB is below -10degC and communication between the rover and lander is required.

Insulation of the WEB

The requirements for the thermal design of the WEB were to maintain electronics within ±40degC temperature range in the presence of 5 distinct thermal environments: operations on Earth during test, on the launch pad in configuration with the MPF lander, cruise, attached to the lander upon delivery to Mars, Mars surface exploration. In addition, the WEB was required to meet a mass target of under 2kg, satisfy the 60cm x 48cm footprint of the vehicle, and satisfy a heat leak requirement of under 2W.

Several insulation techniques were considered for the application: Owens-Corning Aura™ vacuum jacketed fiber insulation, polyurethane foam, opacificed aerogel powder encapsulated in Nomex honeycomb core, and solid silica aerogel in a sheet and spar structural design. The nonrigidized vacuum bottle concept of Owens-Corning Aura™ essentially uses thin metal sheets sealed around evacuated fiberglass insulation. Although acceptably low in conductivity, the edge effects of the individual small panels were impractical given the need for additional mass to support the design. The polyurethane foam was bulky and the required amount for the thermal design could not be satisfied within the volume and mass constraints of the rover. The design developed using the opacified aerogel powder in the Nomex honeycomb had acceptable thermal performance characteristics. However, two problems emerged when a WEB of this design was built. The opacified aluminum added to the aerogel powder available commercially resulted in a bulk density of 160mg/cc. The resulting insulation did not meet the mass requirement. In addition, initial dynamic testing of the WEB with this design showed a tendency for separation of the material resulting in 'cold spots'. Although this was most prevalent in weightless conditions which could be addressed by other means during cruise, another design was considered.

The solid silica aerogel was selected as the insulation material for the MFEX rover due to positive experimental and analytical results for thermal conductivity and bulk densities in manufacture of 20mg/cc which offered promise of meeting the mass requirement. This selection was not without its own problems, since the material at this density was produced in an autoclave unique to a JPL technology program and only in quantities sufficient for use in a proposed sensor program[3]. Also this decision was reached only after the above approaches had been rejected: the approaches used in developing the cost estimate for the project. The time was 18 months (3/94) into the project and a WEB of an acceptable design was due for initial integration with other rover components within 9 months (12/94). A significant design and development effort by MFEX engineers and technologists ensued, resulting in the manufacture of a WEB for evaluation and test (1/95). The success of the first thermal environment and dynamics test kept MFEX rover integration on schedule but at the cost of the first significant allocation of reserves.

Software Development Model

Prior to the initiation of the MFEX project a Rocky vehicle had been demonstrated performing a science mission resembling the initially planned investigations for the MPF mission. The success of this demonstration established a technology baseline for the MFEX project. But also resulted in the delivery of the Rocky vehicle (Rocky 4) to the project.

Rocky 4.1 was the Rocky vehicle stripped to the bare chassis for mobility testing in sand and lunar simulant. Motors and mechanisms which were close analogs of those considered for the flight rover were added for these tests. Rocky 4.1 was then upgraded with a wire-wrap computing breadboard, the gyro and accelerometers selected for the flight rover, commercial cameras and laser stripers, and the RNET radio modem. This vehicle (Rocky 4.2) became the testbed for software development. The basic navigation and hazard avoidance algorithms, motor and vehicle control strategies, the communication protocol, command and telemetry formats, and the memory management and processing architecture of the MFEX rover was developed on this testbed. A version of this software was running on Rocky 4.2 by the end of the first year of the project and evaluations in a sandbox were conducted.

When the first Maxon motors and gearboxes intended for the MFEX rover were available, Rocky was retrofitted becoming Rocky 4.3. Software development continued with upgrade of the vehicle control and monitoring algorithms. In addition, Rocky 4.3 supported the first end-to-end data system test conducted by the MPF project. In this test, communication between Rocky, a testbed version of the MPF flight computer and the first version of the ground data system established the functionality of this part of the mission data flow and allowed interface agreements among the various systems to be involved to be verified. Rocky 4.4 contained the first assembled cameras and lasers of the MFEX rover design and supported the test of the engineering model of the APXS deployment mechanism.

The first prototype computer and power distribution boards for the MFEX rover was developed in a wire wrapped brassboard configuration. When configured with the rest of the Rocky vehicle, this became Rocky 4.5. The mass and volume of this brassboard set of electronics made Rocky 4.5 the first non-mobile vehicle in the Rocky series. However, as a bench top testbed, the interfaces to flight versions of component electronics and the software management of the MFEX rover sensors was verified with Rocky 4.5.

The final prototype in this series was Rocky 4.6 with a discrete wired, printed circuit board version of the MFEX rover electronics. All but a few of the components on these circuit boards were flight parts. The construction of these boards tested the production process for the eventual flight electronics boards for the MFEX rover and were the functional and physical equivalent of these boards. While the evaluation model of the MFEX rover was being constructed (the System Integration Model rover or SIM) Rocky 4.6 was the testbed for the flight software. The timing and interface protocols to all electronics were developed and tested. The structure, size and data management employed by the flight software was verified on Rocky 4.6 and this vehicle participated in the final phases of the end-to-end information system tests prior to the initiation of the Assembly, Test and Launch Operations (ATLO) for the MPF project.

Rocky serves as the best example of the ‘rapid prototype’ process used by the MFEX project. Throughout the entire course of the project a ‘version’ of the eventual flight vehicle was available for software development, system test and evaluation purposes.

SYSTEM INTEGRATION MODEL (SIM)

The final steps of the implementation process used by the MFEX project was the development in tandem of two rover vehicles : the ‘System Integration Model’ or SIM and the Flight Unit Rover or FUR.

The SIM was intended as the engineering or evaluation model of the eventual MFEX rover. All assembly procedures, environment tests, functional tests, fit checks, cleaning procedures and ground support equipment development were first checked on the SIM before being applied to the FUR. Since the SIM and FUR were constructed to the same set of blueprints, the test experience of the SIM was a direct analog to the eventual performance of the FUR under similar test conditions. The usual ‘qualification level’ test conditions were applied to the SIM: temperature extremes 15degC beyond the expected nominal conditions, static load conditions 3 sigma above predicts, dynamic loads a factor of 2 above those established for flight acceptance, etc. All but one test was passed by the SIM, giving confidence that the FUR when exposed to ‘flight acceptance levels’ of the same tests would pass without a problem.

The one test case failure occurred during the centrifuge test of the SIM. In the tie-down configuration of the rover to the MPF lander petal, wheel cleats mesh to similar material on the mounting hardware on the petal. Due to wear of the cleats through the extensive series of functional tests (the centrifuge was the last environment test of the SIM), cleat bonds failed and a wheel released on the final axis of the centrifuge test, rotating around the wheel cages to strike and damage the SIM solar panel. This led to a redesign of the wheel cleats and the introduction of rivets to augment the cleat bonds. The wheel of this revised design was tested with the FUR in a centrifuge test at the flight acceptance levels and the FUR passed this test without incident. The SIM with the revised wheel cleats will be tested again at the qualification levels for static loads.

With the assembly, test and delivery of the FUR to the MPF project completed, the SIM has become the testbed supporting software parameters tuning, operations planning and personnel training for the operation phase of the Pathfinder mission. As a part of these activities, the SIM will undergo field testing in outdoor test facilities at JPL and elsewhere, demonstrating the robustness of the mobility, navigation and hazard avoidance systems.

As testament to the benefit of this implementation approach, the FUR was integrated with the MPF lander without a problem, satisfying all mechanical and electrical interface requirements. The software delivered with the FUR has been shown to work with the MPF lander flight computer software and ground system. All can be attributed to the incremental test and development approach employed by MFEX.

SUMMARY

The 'rapid prototyping' approach of the MFEX project has proved successful in leading to the delivery of the MFEX rover to the MPF flight system. As can be seen in Fig. 2, the cost incurred by the project at time of this delivery is roughly two-thirds of the available resources.

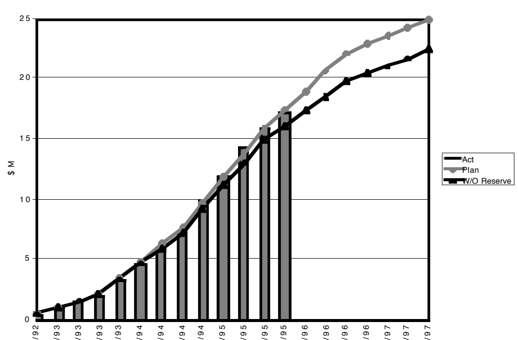

Fig. 2 MFEX Cost Performance

The implementation plan developed during the first year of the project and presented at the MPF project Design, Implementation and Cost Review (DICR) has proved remarkably accurate. The small reserve of the MFEX project (less than \$3M of the \$25M cost cap) and only available after the first year of the project has been sufficient to address problems in the development and test program conducted by the project. As the first flight microrover development, the MFEX project has shown that a technology development can be taken through implementation in the span of 40 months using the approach described herein. The small MFEX engineering staff looks forward to the launch and operation phase of the mission.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Bickler, D. B. (1992). A New Family of Planetary Vehicles, International Symposium on Missions, Technologies and Design of Planetary Mobile Vehicles, Toulouse, France.
2. Gat, E. et. al. (1994). Behavior Control for Robotic Exploration of Planetary Surfaces, IEEE Journal of Robotics and Automation, 10(4):490-503.
3. Hickey, G.S., et. al. (1995). Integrated Lightweight Structure and Thermal Insulation for Mars Rover, 25th International Conference on Environmental Systems, July 11-15, 1995, San Diego, Ca.
4. Shirley, D. (1993). MESUR Pathfinder Microrover Flight Experiment: A Status Report, Case for Mars V Conference, Boulder, Co.
5. Shirley, D. (1994). Mars Pathfinder Microrover Flight Experiment - A Paradigm For Very Low-Cost Spacecraft, IAA-L-0506, 1st International Conference on Low-Cost Planetary Missions.
6. Wilcox, B. et. al. (1986). Computer Aided Remote Driving, AUVS-86, Boston, Ma.
7. Wilcox, B. et. al. (1988). Mars Rover Local Navigation and Hazard Avoidance", Proc. SPIE Conf. 1007, Mobile Robots III.