MARS ROVERS: PAST, PRESENT AND FUTURE

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Abstract

Since the 1960's there have been efforts world-wide to develop robotic mobile vehicles for traversing planetary surfaces. Two Lunakhods were successfully operated on the Moon in the early 1970s, but since then there have been no planetary rovers. Developments in mobility, navigation, power, computation, and thermal control have now allowed a small, 11.5 kg rover named Sojourner Truth to be heading for Mars. Sojourner witt explore an area within site of the Pathfinder lander's camera, making measurements of the surface properties, and imaging rocks and obtaining their elemental composition. Future U. S., and perhaps Russian rovers are planned to go to Mars in 2001, 2003, 2007 and 2011 to rove 10 kilometers or so and collect samples for return to earth by missions launched in 2005, 2009 and 2013.

Introduction

On July 4, 1997, earthlings will invade Mars. Mars Pathfinder and its microwave oven-sized rover, Sojourner, will land in an ancient flood channel and try to find out what Mars is made out of. In March of 1998 Mars Global Surveyor will begin a two earth-year mapping mission to study the surface and atmosphere of the red planet. These missions will be followed every 26 months by additional missions to search for water and clues to whether life ever began on Mars.[1,2]

The Mars Exploration Program, which was initiated in 1994, is launching two missions every 26 months to Mars to study it from orbit and in detail on the surface. The program, managed by the Jet Propulsion Laboratory for NASA, is currently funded at a total of about $150M per year - or pcr mission - which is about the cost of a major motion picture. This is in contrast to the last Mars mission, Mars Observer, which cost nearly $1 billion including the launch vehicle and operations. Viking, in today's dollars, cost over $3.5 billion.

International participation is an important factor in the program, and relationships are being established with Russia, Europe and Japan.

Since the discovery of possible signs of ancient life in the Martian meteorite ALH84001 last August, excitement about Mars exploration has intensified, NASA and JPL have developed a plan for an expanded program to include returning carefully selected samples from the surface of Mars for analysis on earth. Augmented funding for this program is included in the President's 1998 budget request, but must be appropriated by Congress. Current information on the Mars Exploration Program is available on the Internet a t http://www.jpl.nasa.gov/mars.

The ability to move about the Martian surface is key to the Mars Exploration Program.

The first U.S. robotic planetary rover is Sojourner, (the Mars Pathtinder Microrover Flight Experiment). Sojourner is a NASA technology flight experiment which is currently on its way to Mars.[3]

Rovers in the Past

Sojourner is the culmination of a long line of designs and test models for planetary rovers. Beginning with the first successful planetary rovers, Lunakhod, which roamed the lunar surface in the early 1970's, many countries have been involved in rover research and development. An early focus was on mobility. It was quickly found that six wheels were better than four, with each wheel needing its own motor. U.S. researchers in the 1960's built several versions of possible planetary mobility systems and tested them in the field.

The problem of navigation and control was, however, harder to deal with in the early days. Computers were large and slow and hard to program. Lunakhod, for example, used simple teleoperation so that the operator could "joy stick" the rover to direct it. But Lunakhod proved very difficult to drive: it had only a monocular, black and white camera, and the 3 second round-trip radio delay made driving very counterintuitive and exhausting.

Artificial intelligence was focused on rover navigation by DARPA in the 1980's as part of the Automated Land Vehicle Program. Martin Marietta Corporation and Carnegie Mellon University both built vehicles that could automatically drive on roads and around obstacles. JPL outfitted a HMMV army vehicle to be remotely controlled in rugged terrain,

JPL's technique involved an operator viewing stereo pictures taken by the vehicle and then plotting the vehicle's path and radioing it to the vehicle. The vehicle would then automatically follow that path using a compass and its own vision system. This system was known as "Computer Aided Remote Driving" or CARD.

With improvements in computers came the ability to investigate legs for mobility. Ohio State University built a legged vehicle for the army. Its gait was automated, but it required a driver to direct it. Carnegie Mellon University built several walkers, the most successful being Dante, which descended into the inferno of Mount Spur. Martin Marietta built a model of a simple "beam walker" which involved raising and lowering legs which slid along a beam. Tiny, legged rovers were built by MIT and IS Robotics.

Navigation systems also became more complex. At JPL a "little blue rover" about 6 feet long was used as a navigation test bed. In the late 1980's a computer that could handle autonomous navigation was too big to be carried by the rover, so it dragged cables connected back to a VAX computer in the lab.

In the late 1980's the Mars Rover Sample Return (MRSR) mission studies gave hope to the rover community that at last a rover would go to Mars. The mission was designed to land a pickup-truck sized rover to go hundreds of kilometers, collecting a wide variety of rock samples, and returning thcm to a sample return vehicle to bring back to earth. In order to navigate these rovers high resolution orbital imaging was planned. These pictures would be used for an operator to plan a basic course for the rover, and for the rover to automatically locate itself within the resulting map. This was known as "Semi-Autonomous Navigation" or SAN. Because the computers even in the early 1990's were pretty bulky, the test vehicle for SAN was "Robby" which featured six, one-meter wheels and a large, rugged body to carry its "brain".

In 1988 JPL, Martin Marietta, and FMC Corporation developed three independent designs for integrated control/mobility systems for large rovers, and then compared thcm to develop requirements for the sample collecting rover.[4,5]

Naturally, MRSR required a large sample return vehicle to bring back the 10 kilograms or so of sample that the large rovers would collect. And, also naturally, because so much was invested in each vehicle there should be two of everything to prevent total mission failure caused by any one element: orbiter, lander, rover, ascent vehicle, earth return vehicle. The total price tag for the mission began to approach $ 10B, and in 1991, when Congress slashed all funding for Mars missions - human OR robotic, MRSR was canceled. Rover designs which could "scout" and "survey" sites for human missions were also being studied in the early 1990's. Again, these were large rovers.[6,7,8,9]

In the meantime, work on small rovers was going on. Rodney Brooks at MIT created what he called a “subsumption architecture” for navigation, based on insect behavior. 10 Simple behaviors could be implemented in a simple, light-weight and inexpensive computer. David Miller and his team at JPL built small rovers based on this technique, the first of which was “Tooth”. Don Bickler of JPL developed a six-wheeled mobility system which by hooking the wheels to levers rather than directly to the body allowed a stable platform, suitable for mounting instruments and solar arrays. Don built small models intended to be 1/8 scale for MRSR rovers. They were known as “Rocky”, short for “rocker bogie”. When “Tooth’s” brain was added to Rocky’s body a small, autonomous rover was born.

“Rocky 3“ demonstrated a fully autonomous traverse and sample collection and return to a simulated sample return vehicle in 1990. In June of 1992 a team led by Lonne Lane of JPL demonstrated “Rocky 4“, a small rover which carried out many of the functions which would be required of an actual flight rover: mobility, instrument operation, and goal setting by an earth operator but autonomous path execution and hazard avoidance. Rocky 4 was the starting point for the Mars Pathfinder Microrover Flight Experiment which resulted in Sojourner.[11,12,13]

Sojourner Truth, the Rover

Sojourner, named as a result of a children’s essay contest, is a NASA technology demonstration flight experiment which is integrated with the Mars Pathfinder (MPF) lander and was launched on December 4, 1996. After landing on Mars July 4, 1997, the MFEX rover will deploy from the lander and conduct a series of experiments which will validate technologies for an autonomous mobile vehicle. In addition, Sojourner will deploy its science instrument, an alpha proton x-ray spectrometer (APXS), on rocks and soil to determine the elemental composition. Lastly, the rover will image the lander as part of an engineering assessment after landing.[14,15]

Sojourner Description

Sojourner (see Fig. 1) is a 6-wheeled vehicle, 10.5 kg in mass (including payload), and 65 cm long, 48 cm wide and 30 cm tall in its deployed configuration (neglecting the height of the UHF antenna), The rover is stowed on a lander petal for launch and during the cruise-to-Mars phase of the Pathtinder mission. In this stowed configuration, the rover height is reduced to 19 cm. In this configuration, the rover has been tested and shown to withstand static loads of 66g, consistent (with margin) with the less than 40g expected at impact upon landing on Mars. At deployment, the lander fires cable cutting pyres, releasing tie-downs which restrain the rover to the stowed configuration. Under command, the rover drives its wheels, locking the bogeys and deploying the antenna so that the deployed configuration is achieved.

In the deployed configuration, the rover has ground clearance of 15 cm, The distribution of mass on the vehicle has been arranged so that the center of mass is slightly aft of the center of the body (the Warm Electronics Box (WEB)) and at a height at the base of the WEB. Due to the innovative design of the rear differential which transfers wheel angle to half-angle tilt of the WEB the vehicle could withstand a tilt of 45 deg in any direction without over-turning, although fault protection limits prevent the vehicle from exceeding tilts of 35 deg during traverses.

The rover is of a rocker bogie design[16] which allows the traverse of obstacles of up to 17 cm (more than a wheel diameter (13 cm) in size). Each wheel has cleats and is independently actuated and geared providing for climbing in soft sand and scrambling over rocks. The front and rear wheels are independently steered, allowing the vehicle to turn in place. The vehicle has a top speed of 0.4m/minute and can turn at a rate of 7 deg/sec.

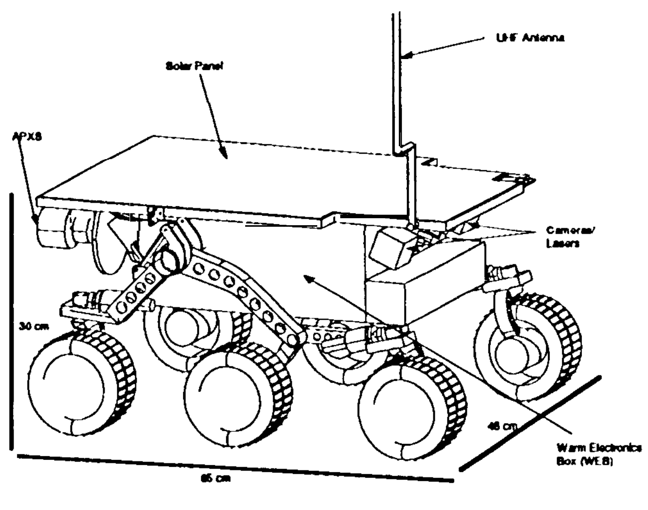

Fig. 1. Mars Pathfinder Microrover

The rover is powered by a 0.22 sqm solar panel comprised of 13 strings of 18, 5.5 mil GaAs cells each. The solar panel is backed up by 9 LiSOCL2 D-cell sized primary batteries, providing up to 150W-hr of energy. The combined panel and battery system allows the rover to draw up to 30W of peak power while the peak panel production is 16W. The normal driving power requirement is 10W.

Rover components not designed to survive ambient Mars temperatures (-800 deg C during a Martian night at the Pathfinder landing site) are contained in the warm electronics box (WEB). The WEB is insulated with solid silica acrogel, has an exterior finish of gold-coated kapton, and is heated under computer control during the day. This design has been verified in both stand-alone and integrated (with the lander) environment tests showing that the WEB maintains components between -40 deg C and +40 deg C during all mission phases including Mars landed operations. These test have led to the development of a thermal model of the WEB with performance under a variety of environment conditions.[17]

Computer control is implemented by an integrated set of computing and power distribution electronics. The computer is an 80C85 with a 2 MHz clock rated at 100 Kips which uses, in a 16 Kbyte page swapping fashion the memory provided in 4 different chip types.

At boot up or upon reset the computer begins execution from the PROM. The programming stored in PROM loads programs into the RAM (IBM 2568 chip set) from non-volatile RAM (SEEQ chip set). Program execution proceeds from the RAM. As commands arc executed, other programming in non-volatile RAM is required and then swapped into the RAM for execution. To prevent excessive thrashing, some programs are executed from non-volatile RAM. While programs are executed, data is stored in temporary RAM storage area (Micron chip set). Telemetry generated during program execution is regularly transmitted to the lander for relay to earth. If communication with the lander is not available, telemetry is stored in a FIFO rotating buffer, reserved in the temporary RAM storage area. At boot up during night operations, provision for data storage in non-volatile RAM is provided. Such data is sent as telemetry to the lander when a communication opportunity permits.

The remainder of the electronics supports switching, power conditioning, and I/O channels.

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 determines 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. While stopped, the computer also updates its measurement of distance traveled and heading using the average of the number of turns of the wheel motors and an on-board gyro. This provides an estimate of progress to the goal location.

Command and telemetry is provided by UHF radio modems on the rover and lander. The modems arc capable of 9.6 Kbaud transmission. Overhead associated with the protocol in data transmission and the effective link performance results in 2 Kbps transmission. Estimates of the amount of telemetry data transmitted by the rover during its operations is given below. In general, most of engineering data collected by the rover supports technology experiments. The amount of experiment data listed is aggregates for all science, technology and mission experiments, although not all experiments are scheduled to be performed each SOL The available data volume between the lander and rover is 14.4 Mbit and is based on 2 hour of continuous transmission during a given sol. In these estimates no 'overhead' data (e.g., header, frame protection, retransmission of frames) is included.

Sojourner's Mission

During the day, the rover regularly requests transmission of any commands sent from earth and stored on the lander. When commands arc not available, the rover transmits any telemetry collected during the last interval between communication sessions. The telemetry received by the lander is stored and forwarded to the earth. In addition, the communication system is used to provide a 'heartbeat' signal during vehicle driving. While stopped the rover sends a signal to the lander. Once acknowledged by the lander, the rover proceeds to the next stopping point along its traverse.

The rover's mission consists **of:** (1) conducting a series of experiments which validate technologies for an autonomous mobile vehicle, (2) deploying an alpha proton x-ray spectrometer **(APXS),** on **rocks** and soil, and (3) imaging the lander as part of an engineering assessment after landing. The rover's mission plan for the first week on Mars is shown in Fig. 2.

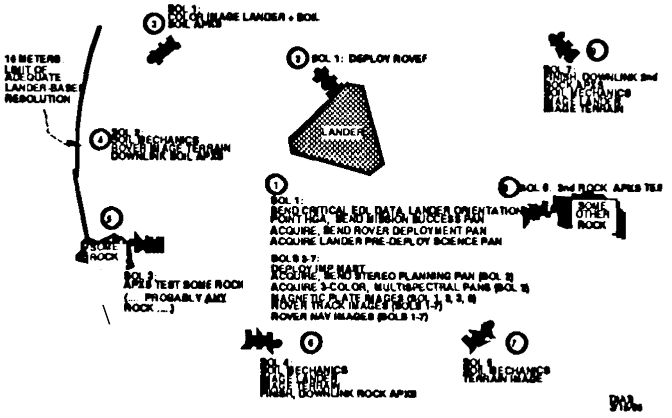

Fig. **2.** Mars Pathfinder lander and rover: nominal 7 sol scenario

The first sol on Mars will be devoted to the release and deployment of **Sojourncr** from the lander, and the acquisition of an **APXS** measurement on soil. If possible, the end of sol imaging performed by the rover **will** include a portion **of** the lander. The next two (as **neccssary)** SOIS will be used to acquire an APXS measurement of some rock in the vicinity of the lander. Along the traverse to the rock, a soil mechanics technology experiment will be **pcrformcd.** With success, SOIS 4-6 will be devoted to positioning the APXS for measurement of a specific rock: the rock selected through an evaluation of the panoramic image of the landing site taken by the lander camera, Along the traverse to this rock, another soil mechanics technology **cxpcrimcnt** wilt be **pcrformcd,** in a second soil type. In addition, images from the rover will be taken of recks, soil and terrain to assist in the terrain reconstruction at the landing site. Images of the lander will be taken in an attempt to complete a full survey. The remaining sol in the 7 sol nominal mission will be devoted to ensuring data has been collected for all the technology experiments while Sojoumcr is traversing to another rock or other objectives in the **cxtcndcd** mission.

Technology Experiments

The primary function of Sojourner is to demonstrate that small rovers can actually operate on Mars. Until at least 1995 there was considerable skepticism by the science community that the capabilities of such a small rover to collect science were worth the $25M investment in the rover. Therefore, Sojourner will perform a number of experiments to evaluate its performance as a guide to the design of **future** rovers. The performance of these experiments on Mars will assist in verifying engineering capabilities for future Mars rovers, completing a data set which includes environment and performance testing conducted with Sojourner prior to launch and with the spare rover (Marie Curie) on earth in parallel with Sojourner's experiments on Mars. The technology experiments are listed below:

- Mars Terrain Geometry Reconstruction from Imagery - Each sol, images are taken by the rover and lander as a means of planning the next sol of operations. As a collection these images will be used to **construct** a map of the landing site.
- Basic Soil Mechanics - In a soil sample, as a single front or rear **whccl** is **turncd** in place, **the** motor current is measured and an estimate of torque is derived.
- Dead Reckoning Sensor Performance and Path Reconstruction/Rccovcry - The telemetry logged by the rover during traverses provides a means of reconstructing the path traversed by the **vchiclc.**
- Sinkage in Each Martian Soil Type - At the end of selected wheel rotations performed during the soil mechanics experiment, images of the resulting rut are taken.
- Logging/Trending of Vehicle Performance Data - During vehicle operations, **enginccring** measurements **arc** taken regularly which **will** help to verify rover performance.
- Rover **Thcrmal** Characterization - The rover has 7 **tcmpcraturc** sensors internal to the WEB and 6 external sensors. These sensors will be sampled during both day and night each sol in tracking the thermal characteristics of the vehicle.

- Rover Imaging Sensor Performance - Engineering telemetry gathered during traverses arc the primary means for the reconstruction of paths taken by the rover across the terrain and evaluation of the navigation and hazard avoidance systems.
- UHF Link Effectiveness - The rover routinely communicates with the lander, transmitting telemetry and receiving commands. Data transfer errors will be logged to develop a model of the UHF link effectiveness.
- Material Abrasion - Wheel material wear can be correlated to the amount of abrasion caused by Martian soil per distance of wheel travel,
- Material Adherence - Power from a "clean" solar cell will be compared with that from a "dusty" cell. The correlation bet wccn the amount of dust and cell output measure the effect of dust on solar panel performance during the mission.
- APXS - In addition to the technology experiments the Alpha Proton X-Ray Spectrometer and the visible and near infrared filters on the lander imaging system will determine the elemental composition and constrain the mineralogy of rocks and other surface materials at the landing site.
- Lander Assessment - During the mission, the rover cameras will be used to image portions of the lander.

After landing, Sojourner will be deployed from the lander and begin a nominal 7 sol (1 sol = 1 Martian day) mission to conduct its experiments. This mission is conducted under the constraints of a once-per-sol opportunity for command and telemetry transmissions between the lander and earth operators. As such, Sojourner must be capable of carrying out its mission with a form of supervised autonomous control, in which, for example, goal locations are commanded and the rover navigates and safely traverses to these locations.

Sojourner's Operation

The operation flow for the rover is driven by a daily command load from earth via the lander. These commands are generated at the rover control station, a silicon graphics workstation which is a part of Pathfinder's ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the rover vehicle in the terrain. Those images, portions of a terrain panorama and supporting images from the rover cameras are also displayed at the control station. The operator is able to designate on the displayed image(s) points in the terrain which will serve as goal locations for rover traverses. 18 The coordinates of these points are transferred into a file containing the commands for execution by the rover on the next sol. This command file is incorporated into the lander command stream and is sent by Pathfinder ground control to the lander for transmission to the rover.

Engineering telemetry which is transmitted from the rover to the lander is transmitted by the lander back to earth on a priority basis, including lander images and rover position data needed to develop the command sequence for execution on the next sol. Analysis of this telemetry is conducted through the rover engineering team's workstations.

In this telemetry analysis an engineering go/no-go decision is reached concerning the execution of a nominal "next sol" sequence of rover activities (e.g., see Fig. 2 for the first 7 sols). In the presence of a "go", a brief review of the mission objectives of the next sol of rover operation is performed by members of the experiment teams. Any modification of targets of opportunity (e.g., locations for soil mechanics experiments, rock selected for eventual placement of the APXS) based on a review of the images from the prior sol is evaluated as part of a trafficability and mission time assessment performed by engineering personnel and the rover operator. An agreement on the targets of opportunity results in an update (perhaps) of the sequence of rover activities. This update is used by the rover operator to prepare the command sequence for submission to the rover. A review of the sequence (in a human readable form) by experiment and engineering personnel both for the rover and the Pathfinder mission represents the final check (and edit) before transmission,

Autonomous Control

In order to accomplish the mission objectives, the rover must traverse extended distances within the vicinity of the lander. The once-per-sol commanding strategy of the mission require that the rover perform these traverses essentially unsupervised by earth-based mission control. The rover uses a strategy of on-board autonomous control which allows the commanding of high-level, goal-oriented commands supported by a hazard avoidance system.[19,20] In this system the rover attempts to determine where to go, drive toward the location, avoid obstacles along the route and decide when (or if) it has made sufficient progress to the goal.

The rover performs a traverse by executing a "go_to_waypoint". During the traverse, the rover updates its position relative to the lander to determine (at a minimum) if it has reached the goal location. This update is accomplished using the encoder reading on the wheel actuators. The counts accumulated on each of the six wheels are averaged to determine a change in the odometer. This averaged value is used to update the estimated vehicle position in the lander-ccntcrcd coordinate s ystcm.

To change heading the rover executes a command to "turn. The four outside wheels arc cocked to a 'steer-in-place' orientation through driving the steering actuators to the appropriate position as measured by the potentiometers on each actuator, and the wheels arc driven. Once the commanded orientation is achieved, the integrated angular measurement from the gyro is used to update the vehicle heading reference. The "go_to_waypoint" and "turn" commands arc developed by the rover operator using the once-each-sol stereo image of the rover taken by the lander camera.

In achieving the goal locations of its traverse commands, the rover must determine a safe path for traverse at any distance from the lander. The on-board hazard detection system provided by the front camera systcm and laser light stripers illuminate a part of the region in front of the vehicle and the results are correlated to develop a sparse map of obstacle distances and heights in front of the vehicle.

The map is then assessed to determine vehicle trafficability. If a hazard is detected as a result of this assessment, the rover autonomously turns. The hazard detection and assessment is then repeated until a clear path is identi fied. The rover is then autonomously driven past the hazard. The goal location again becomes the objective of the traverse and the rover turns back to the proper heading. The rover also measures tilt to avoid slope hazards.

Each 'go_to_waypoint' command executed in a traverse has as a parameter a time value for execution. During the execution of any command and hazard avoidance activity the rover updates position and orientation. An assessment of progress to the goal location is performed. When the on-board estimates come within a threshold of the goal location, the rover stops, sends telemetry collected during the command execution and proceeds to execute the next command in the operative sequence.

During testing with the vehicle system, the combined navigation and hazard avoidance function has been shown to accumulate an error of approximately 7% of the range of travel. By traversing a sufficient distance MFEX can miss rock destinations. However, a combination of correction in position using lander camera images with a nominal 2-sol (at least) mission plan to reach a specific rock should allow imaging and deployment of the APXS at specific sites.

The successful conclusion of Sojourner's mission will not only result in a great increase in our knowledge of the composition and characteristics of the Martian surface, but will provide insight for the design of future rovers.

Future Mars Rovers

In January 1999 the U.S. will launch a lander with a robotic arm to land near the south pole. While this mission has no rover the arm will determine a lot about the soil characteristics in a ncw region by digging a trench. In 2001 a rover much more capable than Sojourner will be sent to Mars. The 2001 rover will be capable of traversing "over the horizon" perhaps 10 kilometers or more, to explore a region of Mars which might contain evidence of past life, and to collect rock and soil samples, The 2001 rover is still very mass, power, volume and cost constrained. It is anticipated that the rover and its payload will mass less than 50 kg and cost no more than $45 M. In order to achieve this great increase in performance for a very modest increase in cost the 2001 rover will be based on technology work currently going on at JPL.

There are two "branches" to this technology development: "Rocky 7" being developed by a team led by Samad Hayati,[2,1] which is primarily a navigation and control development platform: and the Lightweight Survivable Rover (LSR) which is primarily a platform for developing advanced mobility, thermal control and mechanisms. The LSR team is led by Paul Schenker. In FY98 the two platforms will be brought together to demonstrate a robust, relativel y long range mobility and navigation capability with the capability for the rover to survive long enough to travel a long distance over many months. Sampling capabilities will also be demonstrated. An "Announccmcnt of Opportunity" for selection of an integrated payload for the 2001 rover is in preparation and will be released in the summer of 1997.

Also in 2001 there is an opportunity for a joint U.S.-Russian mission to land a Marsokhod (a fairly large, 6 wheeled rover). The mission would be developed, launched and operated by the Russians with communication being provided through U.S. orbiter relays. In 2003 a U.S. rover will be flown, essentially a copy of the 2001 rover with some opportunity for technology upgrades. Upgrades will be minimal within the strict funding limitations of the program.

In 2005 it is currently envisioned that the sample return vehicle would land close to onc or the other of the 2001 or 2003 rovers with their caches of samples. There would be a small, short-range rover carried by the sample return lander to retrieve the cache of samples and bring it back to the return vehicle. The program concept includes at least two more rounds of rovers and sample returns to acquire three distinct samples from different areas of Mars to give a good chance of detecting signs of past or present life. Since sample return is a 3 year round-trip, collecting three samples will not be accomplished until about 2016. Rovers would fly in 2007 and 2011, with sample returns in 2009 and 2013.

Rover Design and Technology Needs

As the Mars Exploration Program progresses the need for more sample diversity and the selection of more specific samples will require continuous improvements in rover mobility, navigation, and sampling capability. To enable roving within the tight cost constraints of the program will require low **mass, extreme power efficiency, and great resistance to** low temperatures. Therefore, ongoing advances in rover technology are required.

Some of these technology needs are:

- Efficient Mass/Volume
  - For Low Cost Delivery
  - For Maximizing Payload
- Tens of Kilometers Travel Capability (In Weeks or Months)
  - Continuous Mobility
  - Improved Navigation (Sensors/Software)
  - Efficient Communication With Orbiters
  - Physical Robustness
- All Season Survival
  - Thermal Protection
  - Efficient Energy Generation/Storage/ Management
  - Robustness to Environment
- Sample Selection/Collection
  - instrument Support (Power/Volume/ Thermal/Data)
  - Improved Instruments
  - Manipulation/Deployment
  - Sample Caching
- Planetary Protection
  - Forward and Backward Contamination Protection

Applicable technology is being developed worldwide. But to make the best use of this technology its development must be directed by rover system design and evaluation. In 1994 Kenton Leitzau of MIT based his master's thesis in Systems Engineering on the development of a process for rover design and evaluation.[22] He stressed the need for standard metrics and evaluation techniques to guide rover technology development and design,

Examples of parameters which need to be considered in rover design and research include:

- Mobility
  - Reduced Gravity Operations
  - Traction
  - Turning Radius
  - Tipping Resistance
  - Slipping Resistance
  - Slope Capability
  - Obstacle Handling
  - Energy Consumption
  - Speed

- Navigation & Control
  - Computation
  - Sensors
  - Obstacle/Hazard Avoidance
  - Speed
  - State Knowledge
  - Energy Consumption
  - Safety
- Science Support
  - Operational Scenario Execution
  - Experiment/Instrument Support
- Autonomy
  - Autonomous Navigation
  - Prioritization/Scheduling
  - Health Monitoring
  - Fault Avoidance/Response
  - Energy Consumption
  - Required Human Interaction
- Environmental Stress Resistance/Robustness, e.g.
  - Vibration
  - Shock
  - Pressure Variation
  - Electromagnetic Interference
  - Vacuum
  - Thermal Cycling
  - Temperature Extremes
  - Radiation

There is a tendency in rover research, as in all research, to focus on individual technologies, e.g. mobility OR navigation OR sample collection. But in order to support the pace of rover development needed to support the Mars Exploration Program a systems approach to rover R&D is required. Mobility techniques which look good by themselves may founder when mated with the needs of navigation or science investigations. And demonstrations which ignore the exigencies of the constraints of actual planetary missions are not very useful.

It is unlikely in the next couple of decades that funds will become available anywhere in the world to fly large rovers to Mars. Therefore, rover research should focus on cost effective, mass and power efficient, high performance machines which are capable of withstanding large g-forces and great extremes of temperature, and operating reliably in dangerous and unknown terrains.

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