Robotic Rovers Aid Mars Surface Exploration

Dr. Antal K. Bejczy
Senior Research Scientist
JPL/CALTECH (retiree)
Pasadena, California, USA
antbej@earthlink.net

Abstract – The twin robotic rovers, "Spirit" and "Opportunity" are still making historic exploration on the surface of Mars when this article is prepared in July of 2004. The motivation of the Mars surface exploration is briefly introduced. The twin rovers' engineering characteristics together with their onboard science instruments are described. Some major features and findings of the first six months of the ongoing surface exploration mission are summarized. A mission operation software system is quoted in the Epilogue, accessible to the interested public.

1. Introduction

When searching for possibilities of life beyond our "garden planet" Earth in the solar system, scientists choose to *"follow the water trail"* because water – along with carbon – is the basis of all known life on Earth. Mars orbiters – in particular the Mars Global Surveyor (MGS) and the Mars Odyssey (MO) – in the past years revealed many surface features on Mars that strongly appear to have been shaped by *running water* that has since disappeared, and some of it is possibly buried as layers of ice just under the surface. Scientists also envision the possibility that some life forms, possibly very simple microbes, might have gained existence in ancient times when Mars might have been warmer and wetter, and some form of life could persist even today in underground springs warmed by heat vents around smoldering volcanoes. To investigate those possibilities, scientists must learn more about the history of water on Mars. Water-carved landforms are visible from the Mars orbiters, but *the details of the water's story on Mars are locked up in the rocks scattered across the planet's surface.* This simple water trail scientific search strategy motivates the robotic rover missions on Mars.

The first Mars rover mission Pathfinder, landed in 1997 with the small Sojourner rover, and the Mars Exploration Rover (MER) mission in 2003, landed in early 2004 with the identical twin robotic rovers, "Spirit" and "Opportunity." All these rovers were designed as *robotic aids for scientists,* to help understand the mysterious history of water on Mars, and even of possible life-friendly ancient environments there.

2. Landing Sites on Mars

Topographic maps of the Mars surface obtained from the MGS orbiter measurements revealed that the northern hemisphere of Mars is several kilometers lower while the southern hemisphere is several kilometers higher than the average. The difference from the lowest to the highest point on Mars is over 30 kilometers. Ancient streambeds are visible on the southern hemisphere, carved by ancient water flowed into the huge low-lying northern basin. Ideal landing sites would then be near the Martian equator within the transition area from the higher to the lower elevations, to follow the global flow direction of ancient water on the surface. Out of the some 150 potential acceptable landing sites two were selected: *Gusev Crater* and *Meridiani Planum.* Both satisfied all safety criteria for *airbag-cushioned bouncing landing* and also offered significant evidence of past liquid water, but in two very different ways.

The Gusev Crater, where the Spirit robot rover successfully landed on January 3, 2004, is an impact crater about 150 kilometers in diameter and about 15 degrees south of the Mars' equator. It lies near the transition from the ancient highlands in the south to the smoother plains in the north. A 900 kilometers long zigzag valley enters the crater from the southeast. Scientists believe that this valley has been eroded long ago by flowing water, and the water likely cut through the crater's rim and filled much of the crater, creating a large lake not unlike crater lakes on Earth. The lake is gone long ago, but the floor of the Gusev crater may contain water-laid sediments that still preserve a record of what conditions were like in the lake when the sediments were deposited.

The Meridiani Planum area, where Opportunity successfully landed on January 24, 2004, is near the Mars' equator and halfway (about 180 degrees) around the planet from Gusev crater where Spirit landed. It is one of the smoothest, flattest places on Mars, and has a scientific appeal based on thermal emission spectrometer data from the MGS orbiter. These data have shown that Maridiani Planum is rich in an iron oxide mineral called *gray hematite* which is found on Earth, where it is usually – though not always – forms in association with liquid water.

It took about a week after landing to test and prepare each robot rover's subsystems remotely from Earth, and declare the rovers ready to roll off from their landing platforms and start the history-making exploration journeys on Mars with all onboard capabilities in full health.

3. Science Objectives and Instruments

NASA listed the MER mission's science objectives in eight points. The essence of the eight points can be summarized as follows: *Search for and characterize a diversity of rocks and solids that hold clues to past water activity* (water-bearing minerals and minerals deposited by precipitation, evaporation, sedimentary cementation, or hydrothermal activity). Then, *extract clues from the geologic investigations*, related to the environmental conditions when liquid water was present, *and assess whether those environments were conducive for life.*

Each of the twin robots, working as a remotely instructed *field geologist* is equipped with a package of science instruments relevant for geological investigations along the science objectives. Both robots have identical structure, instruments and functional capabilities. Details of the science instruments are summarized below, and also see Figure 1. **(Figures are at the end of this article.)**

Panoramic Camera System uses two high-resolution color stereo cameras, complementing the rover's navigation camera system.
Mini Thermal Emission Spectrometer sees infrared radiation emitted by objects, and helps determine from afar mineral composition of surface features.
Microscopic Imager is a combination of a microscope and a camera, producing close-up views (on the scale of hundreds of microns) of rocks and soils.
Moessbauer Spectrometer is designed to determine with high accuracy the composition and abundance of iron-bearing minerals.
Alpha Particle X-Ray Spectrometer accurately determines the elements that make up rocks and soils.
Rock Abrasion Tool (RAT) when positioned against a rock by the rover's arm, uses a grinding wheel to remove dust and weathered rock, exposing fresh rock underneath.
Magnet Arrays collect airborne dust for analysis. (Some dust can be magnetic.)
Calibration Targets fixed on the rover serve imagers and science instruments.

Note that the twin "robotic field geologists" also perform some typical laboratory analysis functions on the field sites of Mars and send *analytic data* back to scientists on Earth.

4. Engineering Features of Rovers

Each twin robot is 1.6 meters long and weighs 174 kilograms. Each carries all equipments for telecommunication, computer and camera functions. They do not interact with heir landers once they rolled off. The landers were only holding the rovers, and remained passive structures after the rovers departed from them.

The core structure of the rovers is made of composite honeycomb material, insulated with a high-tech material called “aerogel.” This core body, called the warm electronics box, is topped with a triangular surface called the equipment deck. The deck is populated with three antennas, a camera mast and a solar cells panel. Extra solar panels are connected by hinges to the edges of the triangle surface deck. These extra panels fold up to fit inside the lander during the trip to Mars, and deploy after landing to form a total area of 1. 3 square meters of three-layer photovoltaic cells. (See Figure 1.) Each layer is of different materials: gallium indium phosphorus, gallium arsenide, and germanium. The area can produce 900 watt-hours of energy per Martian day (called sol). After the prime mission time (after the first three months) the energy generating capability is reduced to 600 watt-hours per sol because of accumulating dust and change in seasons on Mars. The solar array repeatedly recharges two lithium-ion batteries inside the warm electronics box.

Each rover is equipped with a six-wheel drive. A rocker-bogie suspension system, which bends at its joints rather than using springs, allows rolling over rocks bigger than the wheel diameter of 26 centimeters. The rovers’ mass distribution is so that the center of mass is near the pivot point of the rocker-bogie system, which enables the rover to tolerate a tilt up to 45 degrees in any direction without overturning, though onboard computer programs prevent tilts more than 30 degrees. Independent steering of the front and rear wheels allows the rover to turn in place or drive in gradual arcs. (See Figure 1.)

The robot rovers have navigation software and hazard-avoiding capabilities to make their own way toward destinations identified to them in daily sets of commands. They can move up to 5 centimeters per second on a flat hard ground, but under automated control with hazard avoidance, they normally travel at an average speed about one fifth of that.

Two stereo pairs of hazard-identification cameras are mounted below the deck: one pair at the front and the other at the rear of the rover. Besides supporting automated navigation, the one at the front also provides imaging of what the rover’s arm is doing. Two other stereo camera pairs sit high on the mast rising from the deck: the panoramic camera system is included in the science package, and a wider-angle, lower resolution navigation stereo camera pair. The mast also serves as a periscope for the miniature thermal emission spectrometer. (See Figure 1.)

Four science instruments (two spectrometers, microscopic imager, and rock-abrasion tool) are mounted at the end of an arm called “instrument deployment device.” (See Fig.1.) It sits under the rover’s front while the rover travels, and extends forward when the rover is in position to examine a rock or soil patch.

The computer in both robot rovers runs with a 32-bit Rad microprocessor, a radiation-hardened version of the PowerPC chip, operating at a speed of 20 million instructions per second. Onboard memory includes 128 megabytes of RAM, augmented by 256 megabytes of FM, and smaller amounts of other non-volatile memory, which allows the system to retain data even without power.

Batteries and other components that are not designed to survive cold nights on Mars (minus 105 C!) are located in the warm electronics box. Heat inside the warm electronics box comes from a combination of electrical heaters, heat given off by electronic components, and eight radioisotope heater units with one watt heat capacity per unit. (Each radioisotope heater unit contains 2.7 grams plutonium dioxide pellet, about the size of the eraser of a standard pencil. Each pellet is encapsulated into a safety box. The safety of this heater technology has been tested extensively, and has been used on other spacecrafts, including the Sojourner rover on Mars in 1997.)

A rover-mounted UHF antenna enables communication of Spirit and Opportunity at 128 Kilobits per second rate with the two Mars Orbiters (MGS and MO) when each of the two orbiters pass overhead. R/T communication direct-to-Earth with the two robot rovers is possible through a high-gain antenna on the rovers in critical cases. But most of the data from the rovers can be relayed to Earth via the two quoted Mars Orbiters.

5. Achievements and Some Exploration Results

Both robot rovers successfully completed their originally planned 90-day mission already in April, and currently are working on extra assignments concurred by NASA and lasting till the end of September this year, which is the start of the serious, very dusty winter season on Mars. - The twin robot rovers on Mars generated worldwide attention and interest as documented by the more than 6 billion registered calls at their NASA/JPL homepage during the first 80 mission days on Mars. By the end of April, Opportunity sent home 15.2 gigabits of data about Mars, including more than 12 thousands images. Similar amount of data and images was received from Spirit during the first 90 days on Mars.

The excellent performance of the onboard autonomous navigation software of the twin rovers during the first three months motivated the ground controllers to upgrade this software in May. This upgrade expanded the rovers' options for extended onboard planning and routing, yielding faster progress toward a designated area. As a consequence of the upgrade, Spirit rover's odometer on July 16 already registered 3.5 kilometers total travel after landing, which is four times the rover's designed travel expectation.

The twin rovers during the past six to seven months consistently used all their onboard science instruments to obtain very valuable analytic data on rocks and soil samples carefully selected by geologists on Earth. The rovers also used their wheels to excavate trenches in the soil. Figure 2 shows the image of the result of history's first rock grinding by the rock abrasion tool on Mars, performed by Spirit rover on February 7, 2004. The result is a rock surface patch 45.5 millimeters in diameter and 2.65 millimeters deep, exposing fresh rock interior material for close inspection with microscopic imager and two spectrometers on Spirit's instrument deployment robotic arm. Figure 3 is an image from Spirit's front hazard avoidance camera showing a 7 centimeters deep trench excavated by Spirit's left front wheel on February 20, 2004.

Opportunity's front hazard avoidance camera took the image shown in Figure 4. The image was taken on March 5, 2004 and shows two holes made by the rover's rock abrasion tool. Analysis of the freshly exposed rock with the rover's science instruments on the robotic arm offered evidence that this part of Mars in the Meridiani Planum may have once been drenched in water. Figure 5 is an image taken by Opportunity's microscopic camera on March 8, 2004. It illustrates the science team's interest for details in the process of exploring the history of water on Mars.

In May, Spirit started traveling to a place informally called "Columbia Hills" which at that time was about 1.5 kilometers away from the rover, while Opportunity received the task to investigate an impact crater informally called "Endurance" which is roughly 130 meters across and 20 meters deep. As winter approaches on Mars in July (when this article is prepared), Opportunity continues to slowly move deeper into the stadium-sized crater, and on the other side of Mars Spirit rover is preparing to climb up the Columbia Hills *backward.* This unusual approach to driving is part of a creative plan to accommodate Spirit's one aging front wheel. On July 15 Spirit successfully drove 8 meters along the base of Columbia Hills *backward*, dragging one of its faulty front wheel. Along the way, Spirit drove over what scientists had been hoping to find in the hills – a slab of rock outcrop that may represent some of the oldest rocks observed in the mission so far. On July 19 Spirit was already higher up in the Hills, having an up-close look at the rock outcrop as seen in the image shown in Figure 6. - In June, Spirit also has been parked near several hematite-containing rocks and conducted science measurements in Gusev Crater which is Spirit's landing place. Hematite is a strong indicator of possible ancient presence of water in that area.

While Spirit climbs higher upward in mid-July, Opportunity is already rolling downward to increasingly deep layers of bedrock lining the walls of Endurance Crater at Meridiani Planum which is Opportunity's landing place. Data from

Opportunity's alpha particle X-ray spectrometer show that chlorine is the only element that dramatically rises with deepening layers, leaving scientists to wonder how it got there. Opportunity's rock abrasion tool (RAT) has nibbled 7 holes into the slope of Endurance Crater while traveling downhill there in June and July. Figure 7 is an image taken by the rover's navigation camera, and shows the 7 holes identified by encircling. Each hole is 4.5 centimeters in diameter.

Opportunity will roll down even farther into the crater to see if the trend of increasing chlorine continues. It also will investigate a row of sharp, teeth-like features dubbed "Razorback," shown in Figure 8, which may have formed when fluid flowed through cracks, depositing hard minerals. Scientist's hope that the new data will help put together the pieces of Meridiani's mysterious and watery past. So far all exploratory surface investigations made by the twin robot rovers point towards an ancient watery past of planet Mars.

By the end of July, the rover planners on the ground start preparing for the Martian winter which peaks in mid-September. Dwindling daily sunshine in winter means that the rovers will have less solar power and take longer to recharge. Periods of rest and "deep sleep" will hopefully allow the rovers to keep working through the winter at lower activity levels to generate more data.

6. Epilogue

An all-important aspect of the twin robot rovers' exploration activities on the Martian surface is the meaningful coordination of the desired scientific investigations and the available technical capabilities onboard, taking account of local environmental constraints that only partly may be known ahead of time. A very elaborate software system, called Science Activity Planner (SAP) was developed to analyze the data received from Mars and help plan the next rover actions, taking account of science interests, rover capabilities, and local constraints. The SAP software package also has powerful visualization features aiding situation perception and activity conceptualization of operating scientists and engineers. – In a public outreach effort, a release of the SAP software (under the name of "Maestro") was made available on-line. It offers the experience to the interested general public to use an actual space mission operation tool that will help understand the many sophisticated aspects of exploratory operations on a distant and partly unknown planetary surface.

Many more information about achievements and results can be found on the Mars Exploration website at www.jpl.nasa.gov – including information about downloading "Maestro."

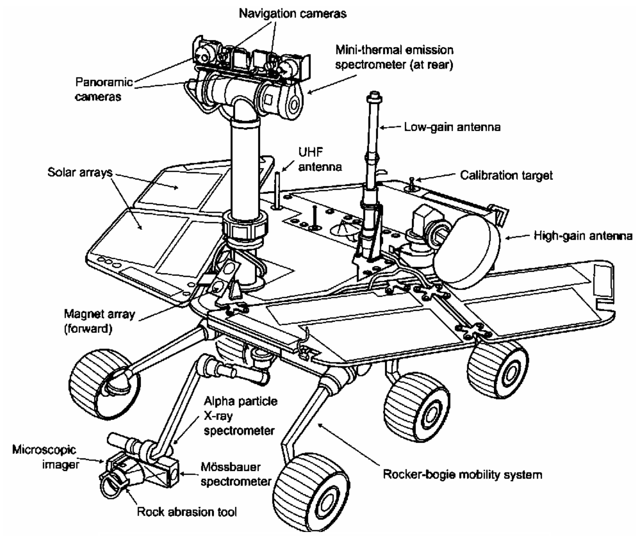

Figure 1. Mars Exploration Rover System

Figure 2. First Grinding of a Rock on Mars
Image from Spirit (Feb.7, 2004)

Figure 3. Spirit Digs a Trench
Image from Spirit (Feb. 20, 2004

Figure 4. Windows to Meridiani's Water-Soaked Past
Image from Opportunity (Mar. 5, 2004)

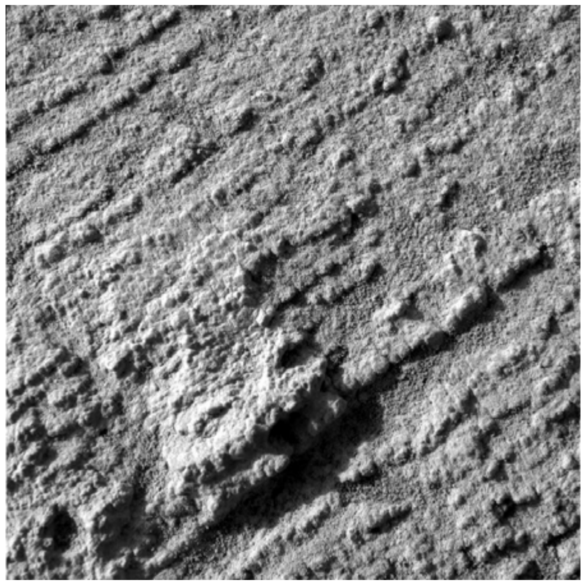
Figure 5. Fleshing out “Flatrock”
Microscopic Image from Opportunity (Mar. 8, 2004)

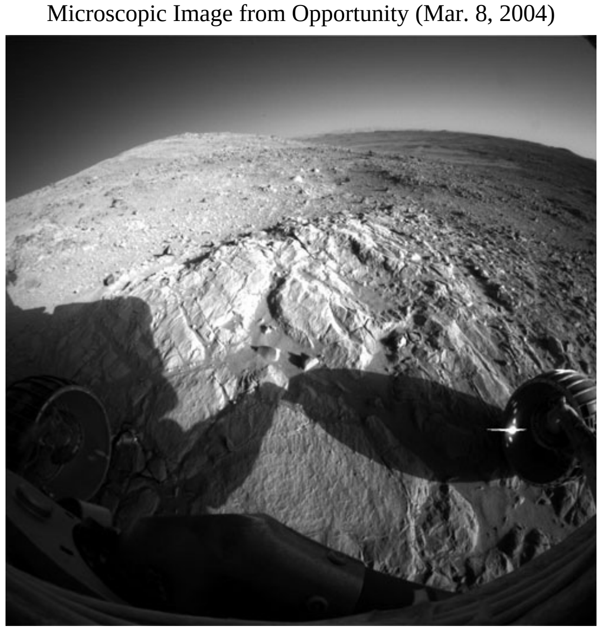
Figure 6. Higher Up in the Hills
Image from Spirit (July 19, 2004)

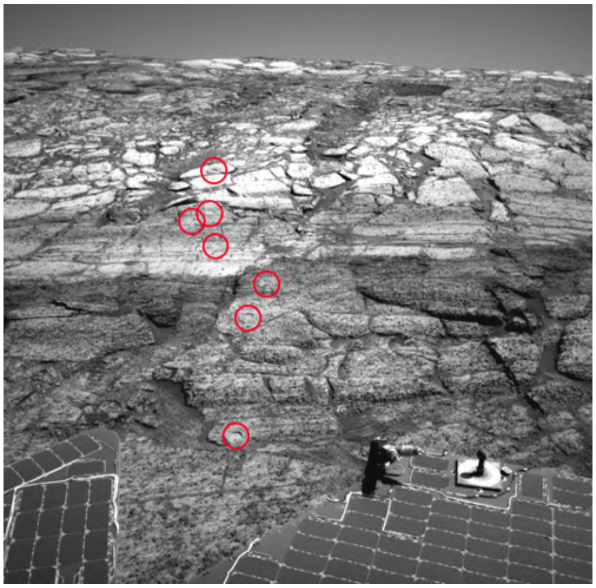

Figure 7. Trail of "Rat" Holes in Endurance Crater
Image from Opportunity (June-July, 2004)

Figure 8. The "Razorback" Mystery in Endurance Crater
Image from Opportunity (July 16, 2004)