EARTH-BASED ROVER FIELD TESTING FOR EXPLORATION MISSIONS ON MARS

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ABSTRACT

The NASA Mars Exploration Rovers mission (MER) involves two robotic vehicles used to explore the geology of two surface regions on Mars in 2004. Prior to its launch, Earth-based field tests and operations campaigns were conducted in the deserts of southwestern USA to physically simulate the mission operations approach planned for MER. A prototype Mars rover called FIDO was used to conduct these field trials in complex geological settings with terrain analogous to the Martian surface at the MER landing sites. This paper provides a high-level overview of the last major field operations test conducted in 2002 leading up to the MER mission. Objectives, approach, general results, and lessons learned are discussed.

KEYWORDS: Mars exploration, planetary rover, FIDO, MER, field test, space robotics

1. INTRODUCTION

As an integral part of initiatives to explore Mars, NASA employs mobile robots that are designed to rove across the surface in search of clues and evidence about the geologic, climatic, and aqueous history of the planet. In early 2004, NASA began a Mars surface mission by landing two spacecraft each carrying a rover to explore distinct regions of the planet's surface. The first rover, *Spirit*, was landed in the Gusev Crater on Mars and second, *Opportunity*, was landed in an area on Mars called Meridiani Planum. These rovers have greater mobility and autonomy than prior NASA rovers and can traverse further distances each Martian day (sol) while conducting more extensive exploration independent of their lander spacecraft. Scientific and technological objectives for the Mars Exploration Rovers mission (MER) are accomplished using the two rovers and the science instrument payloads that they each carry.

During the years leading up to the launch of the MER vehicles, a series of extended field tests and operations campaigns were conducted in the deserts of southwestern USA. The intent was to physically simulate the mission operations approach planned for the MER mission by operating rovers in Earth terrain similar to that expected at the Mars landing sites. Mission operations personnel used a prototype Mars rover for these end-to-end field trials involving networked operations and command workstations, satellite communications equipment, remote field networking and support equipment, and science instrumentation that was fully integrated onboard the autonomous rovers. For each of the field exercises of 2001 and 2002, twenty sols of mission-like rover operational sequences were physically simulated with a focus on developing and rehearsing the MER surface mission operations approach. In each case, the locations chosen by MER scientists were complex geological settings with terrain analogous to the Martian surface. The tests were conducted via satellite from NASA JPL, hundreds of miles from the test site, without prior knowledge of the site location.

This paper provides an overview of a field operations test conducted in August 2002 during development of the MER mission. Results from a prior end-to-end field test are reported in [1]. Objectives, approach, general results and lessons learned are discussed. Key components of the rover systems are briefly described as well as salient differences between the prototype rover used for field tests and the rovers operating on Mars.

2. ROVER OPERATIONS TESTING

The rover mission operations infrastructure is critical to the conduct of a successful remote robotic mission. The infrastructure governs how the rover system will be commanded throughout the mission, how its telemetry will be received and processed, and how the operations team of scientists and engineers will work together to maximize science return while making efficient use of robotic capabilities. As such, it is important to test and refine the processes to be used for operating the rover mission while scientists and engineers rehearse the process under realistic conditions.

In preparation for conducting semi-autonomous rover activities after rover egress from the lander, the 2002 field operations test was performed using the FIDO (Field Integrated Design & Operations) rover. This MER-FIDO field trial brought together planetary scientists, spacecraft engineers and operations personnel, and robotics technologists for active participation in a realistic simulation of rover operations planned for the MER mission. The mission rehearsal involved over sixty science team participants from multiple institutions including NASA, U.S. Geological Survey, and a host of universities (affiliations of MER mission scientists). This team constituted the Science Operations Working Group (SOWG) responsible for conducting the test from JPL. The FIDO system was used to physically simulate a 20-sol mission baseline scenario for the MER *Spirit* rover (Fig. 1) over a period of 10 Earth days. The field venue for the test was an ancient flood plain located approximately 40 miles north of Flagstaff, Arizona USA (almost 500 miles from JPL). At the field site, a small team of field geologists and rover engineers handled all logistical activities. Goals and objectives for the field trial were set based on high-level MER mission requirements to examine how closely they could be achieved using a state-of-the-art rover prototype and best practices gleaned from prior NASA rover field trial experiences.

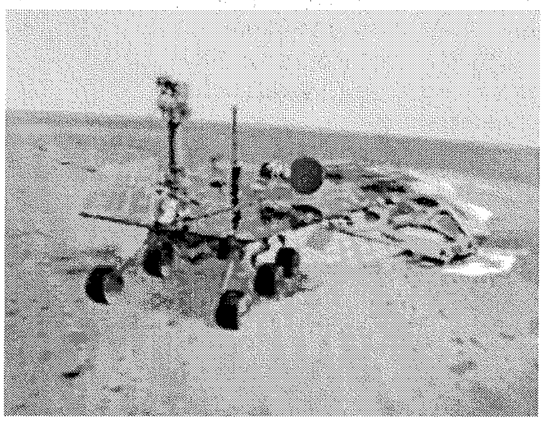

Figure 1. MER Spirit rover on Mars (computer-generated rover and lander models combined with actual Mars 3-D surface data acquired by Spirit's cameras).

2.1 Field Operations Test Objectives and Constraints

The primary objective of the operations testing was for the SOWG to use a remote rover system and rover-mounted instruments to acquire data for formulating and testing hypotheses about the geologic evolution of the field site. Mission operations for the field trial were "blind" and fully remote. That is, the SOWG commanded the rover via satellite communications from JPL, and their prior knowledge of the desert test site was limited to large (tens of square kilometers) aerial thematic imagery and spectral data typical of real Mars orbital observations. The SOWG initially uses the aerial data to generate geological hypotheses about the field site. The rover instruments are then used to correlate hypotheses generated from these additional data to better understand the geology of the field site. This requires use of the rover's capabilities for conducting traverse science and making *in-situ* measurements in realistic terrain subject to mission-like constraints. For example, the objectives were to be achieved subject to realistic uplink/downlink data volumes, separate relay and direct communication links, timing of communications opportunities between the rover and "Earth", distinctions between critical and non-critical telemetry, and strict daily mission operations timelines. A compressed version of the actual mission timeline was followed in order to complete the 20 sols of operations in 10 test days of 9-hour shifts each. For added realism, various types of impromptu anomalies were staged and introduced during operations to exercise SOWG reactions to unexpected events. For all intents and purposes, all mission simulation operations were conducted as if the rover were on Mars, in compliance with MER flight rules and using many of the same rover planning and command functions conducted during the actual MER flight mission.

3. MER PROTOTYPE FIELD OPERATIONS ROVER

The rover prototype used for the 2002 field test was the FIDO rover shown in Fig. 2. This rover represents a central integration platform for the development, rapid prototyping, and testing of advanced robotics technologies at NASA JPL. It is a fully functional prototype that has proven useful to the Mars science community for end-to-end mission concept testing and validation associated with semi-autonomous *in-situ* science exploration via annual terrestrial field trials conducted since the late 1990's. The FIDO rover is not qualified for space flight but it is quite similar to *Spirit* and *Opportunity* in function and capabilities. *Spirit* and *Opportunity* are about 1.5 times larger in size and 2.5 times as massive. Despite differences in size and instrumentation, the similarities of the rovers are significant enough to maintain that the same types of challenges exist in commanding FIDO in complex terrain on Earth, as in commanding *Spirit* and *Opportunity* on Mars. Additional functional similarities and contrasts between FIDO and the MER vehicles and how they are dealt with when physically simulating the MER mission are briefly explained below.

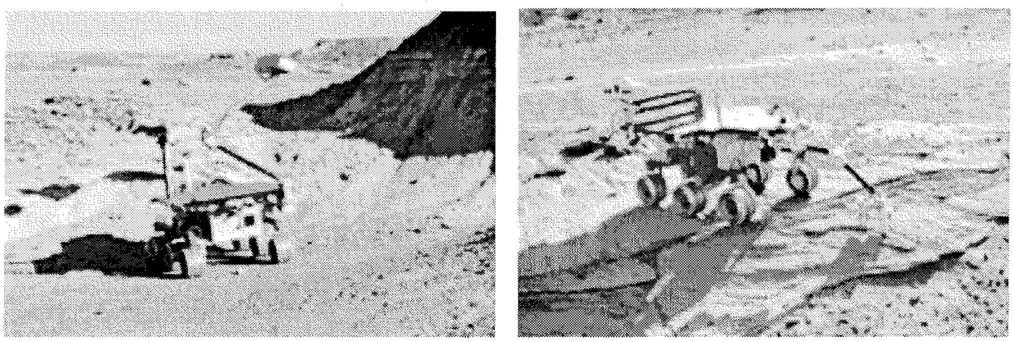

Figure 2. FIDO rover prototype at the 2002 field test site in Arizona.

Solar panels and onboard batteries provide power for the rovers. There are subtle functional differences between the rovers' design and configuration in the areas of mobility and sensing for navigation and control. Both designs employ the JPL 6-wheel rocker-bogie suspension and are compatible with respect to motor control and mobility performance, as well as implementations of inertial and celestial navigation sensing. Engineering cameras on each rover include body-mounted, front and rear stereo camera pairs used for local terrain hazard detection and avoidance during autonomous navigation.

Less subtle differences exist with regard to robotic mechanism designs in three aspects. Firstly, the FIDO rocker-bogie suspension is designed for all-wheel drive and steer, whereas the MER suspension is designed for all-wheel drive and 4-wheel steer. Secondly, the FIDO instrument arm has four degrees-of-freedom (DOF) (and a passive 5th DOF), whereas the MER rover designs employ a five DOF instrument arm. Finally, the rovers each utilize a different type of mast to carry navigation cameras and remote science instruments. FIDO has a 4-DOF mast arm that is deployable to variable heights above its solar panel up to 2 meters above ground at full extent; the 2-DOF MER mast has a fixed height of 1.3 meters above ground after a one-time deployment. It is apparent from Figs. 1 and 2 that the FIDO mast is located at the rear of the vehicle in contrast to the frontal placement of the MER mast, and that the solar array configurations are very different. This results in different near-field obscuration patterns (due to solar panel shape) for the various mast-mounted instruments. To compensate for some of these differences when simulating MER, the FIDO mast was deployed at the MER mast height during field tests (see left image of Fig. 2).

A more distinct contrast between the FIDO and MER rovers is the science payload carried by their respective masts and instrument arms. On its mast, each rover carries a color stereo imaging system for high-resolution terrain surveys, a monochromatic stereo imaging system for planning navigation paths over tens of meters, and an infrared spectrometer for measuring mineral composition of surface materials from a distance (so that rocks/soils can be pre-selected for later close-up investigation). Both rover configurations include a robotic arm beneath the frontal area of the solar panel that carries a suite of instruments used for *in situ* science investigation of terrain surface materials. Each instrument is deployed by positioning the arm to achieve accurate placement onto rocks/soil as required. Each instrument arm includes a microscopic imager to capture extreme close-up images and a Mössbauer spectrometer to detect composition and abundance of iron-bearing minerals. The Mössbauer spectrometer operates using a radiation source, so to mitigate costs associated with radiation safety procedures, FIDO operations involving this instrument were executed using a physical model of the spectrometer. The MER rovers have two additional instruments that are not physically emulated on the FIDO instrument arm. These include an Alpha-Particle-X-Ray Spectrometer (APXS) to determine the elemental chemistry of surface materials, and a Rock Abrasion Tool (RAT) for exposing fresh material beneath dusty/weathered layers of rock surfaces. The FIDO Mössbauer mass model and microscopic imager were used to emulate autonomous *placement* of the APXS and RAT, respectively, during the MER operations test.

More detailed technical descriptions and specifications of the critical FIDO subsystems, mission operations tools, and capabilities can be found in [2-4].

4. APPROACH TO FIELD OPERATIONS TESTING

FIDO field trial mission operators used the MER Science Activity Planner (SAP), a JPL-developed software toolset for collaborative robotic science operations planning [5]. SAP was the primary graphical user interface for uplink planning and command generation as well as downlink data visualization for FIDO. It was used in conjunction with the Parallel Telemetry Processor (PTeP) and the Multi-Mission Encrypted Communications System (MECS), also developed at JPL [9]. Mission operators can command the FIDO rover remotely via command uplink from SAP and receive telemetry data products from the rover and its instrument payload. Telemetry downlink is processed by PTeP and distributed by MECS to remote collaborative SAP users participating in the test across the Internet.

The Planetary Robotics Laboratory at JPL and the SAP, PTeP, and MECS software tools were used for FIDO field operations to emulate the MER mission control area and Ground Data System (GDS). Satellite link capability is available via satellite modem connection between networked computers and a 2.4-meter satellite dish antenna allowing remote commanding of the rover via the Internet. To supplement desktop monitors, operator interface screens are projected onto several large screens in the operations area.

At the desert test site, stand-alone remote equipment infrastructure provides field operations support for the field team and rover. FIDO field support equipment consists of a field trailer containing power supplies, a computer workstation, a laptop command/control computer, an Ethernet hub, a satellite modem, and miscellaneous electronics and mechanical test equipment and tools. The field trailer computers are locally networked and the satellite modem provides connectivity between the trailer network and a 2.4-meter satellite dish antenna set up in the field outside the trailer. Wireless communication between the FIDO rover and the field trailer is accomplished using wireless Ethernet units — one in the trailer and another onboard the rover. Ground truth measurements of the rover position during traverses throughout the field trial are acquired by the field team using a Total Station surveying system (hence the reflecting prism shown mounted on the rover in the left image of Fig. 2). All FIDO rover uplink commands issued from JPL are routed through the laptop command/control computer before transmission to FIDO via the wireless Ethernet. All telemetry from FIDO is stored on the command/control computer and automatically transmitted to the downlink receiver located at JPL.

Typical field trial mission operations activities may be summarized as follows. The SOWG examines available orbital data and makes an initial plan for rover activities that focuses on traversing the field site and making science observations. On the first sol, the rover is commanded to acquire a 360 panorama image mosaic. To begin the second sol, the SOWG examines the panorama data, selects targets of interest and generates the first command sequence, which typically calls for acquisition of more imaging data and IR spectra, as well as deploying the instrument arm to acquire data. The next sequence might include a traverse to the first detailed science target identified by the science team. The rover would autonomously execute the traverse and acquire detailed images and spectra of the target. Similar traversal and measurement activities are repeated throughout the field trial to yield numerous data products including images, spectra, and engineering telemetry. The FIDO onboard software handles all uplink command sequences, autonomous execution under the VxWorks real-time operating system, and downlink of telemetry.

4. MER-FIDO FIELD OPERATIONS RESULTS

The FIDO system enabled the SOWG to plan and execute 20 sols of end-to-end operational sequences proposed for *Spirit*. Activity sequences executed in the field included autonomous traversal to specified targets, approaching rock targets to deploy multiple arm-mounted instruments, and using a rover wheel to excavate soil trenches, including acquisition and analysis of associated imagery and spectroscopy. The SOWG was challenged by the occasional imposition of staged operations anomalies which included temporary full/partial loss of relay or direct communications, reduced available power (due to dusty solar panel or dusty atmospheric conditions), and computing faults that result in reset of the rover computer. Interestingly, some actual unexpected anomalies did occur at the field site during the test which had similar effects (on operations) as the staged anomalies planned for the test. Some of these included an actual dust storm, loss of satellite link due to high winds, as well as erratic rover CPU behavior due to a combination of high winds and low humidity resulting in electro-active soil being blown into vents of the electronics enclosure. In all cases, the operations process remained robust to unexpected anomalies in that necessary planning adjustments were made to continue exploration progress within resource constraints.

FIDO traversed a total integrated distance of 202 meters over the terrain throughout the extended field trial. Its executed traverse paths covered an area of roughly 3 square kilometers at the site. A number of short and long traverses were interspersed among many stationary science investigation activities between intermediate points along the overall traverse. The longest continuous autonomous traverse was ~70 meters, and the average rover speed during traverses was 60 meters per hour while negotiating and avoiding obstacles and terrain hazards. The total data volume (images, spectra, and rover state) downlinked from the rover was 1.6 Gigabytes.

All success criteria were met during the 10-day/20-sol field trial, a subset of which includes: operating FIDO and its science instruments for the equivalent for 20 sols; simulating the daily command uplink and telemetry downlink cycles, data volumes, and critical data prioritization; rover traversal to separate locations (not including the "landing" site) that exhibit distinctly different geologic characteristics; and achieving a total integrated traverse distance of at least 200 meters.

A full account of the 2002 field trial, daily rover operations, and scientific findings can be found in narrative form on the World Wide Web at http://mars.jpl.nasa.gov/mer/fido (for additional detail about the FIDO rover see hyperlinks at http://fido.jpl.nasa.gov).

4.1. Lessons Learned

The experiences and results gained from Earth-based field tests generated a number of lessons learned. Many of the lessons were directly followed in the conduct of MER mission operations and/or led to feature enhancements for GDS or flight software. A few lessons that are most relevant to general robotic operations are mentioned here.

Good process or software tools are necessary for tracking actual end-to-end data flow. That is, the operations process should explicitly track which uplinked commands were actually received by the rover, which downlinked telemetry was actually received on Earth, and what data is stored in rover memory at all times. Tools and process developments were refined with this in mind.

Critical science and exploration decisions are made based, in part, on verbally articulated engineering advice and descriptions of rover functionality and/or capabilities. Interactions between scientists and engineers, therefore, are critical to efficient and productive rover activity planning and operations. As such, effective communication between members of an interdisciplinary team became an important focal point of the MER operations approach.

Finally, although we do not have the luxury of a field team of engineers on Mars missions, a tightly integrated, well-staffed and supported field team is of utmost importance for conducting remote field tests on Earth.

5. SUMMARY AND CONCLUSION

As the space community embarks on future robotic surface missions to other planets or the moon, the utility of Earth-based robotic prototypes becomes more and more important for proving and rehearsing mission operations approaches. This paper provided an overview of the last major field test leading up to the NASA MER mission that employed the terrestrial prototype, FIDO, to emulate one of the flight rovers. High-level details of the 2002 MER-FIDO field trial were covered describing objectives, approach, results, and lessons learned. This operations test, and others conducted in prior years, provided a realistic forum for rehearsing, validating, and refining aspects of the mission operations process, tools, and approach used on MER.

The rover operations infrastructure and its integration with the remote rover system are critical to successful execution of a robotic exploration mission. Tight integration of effective processes and tools enable scientists and engineers to maximize science return through efficient use of robotic capabilities. Earth-based field tests serve in this regard as valuable rehearsals and proving grounds for proposed rover mission operations schemes. They provide opportunities to test robotic activity sequences in realistic settings, train mission personnel on how to use autonomous rovers to conduct remote field-based science, and identify technologies that require additional development and/or evaluation.

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