# Sensing and Perception Challenges of Planetary Surface Robotics

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## Abstract

*This expository paper describes sensing and perception issues facing the space robotics community concerned with deploying autonomous rovers on other planetary surfaces. Challenging sensing problems associated with rover surface navigation and manipulation functions are discussed for which practical solutions from sensor developers would vastly improve rover capabilities. Some practical concerns that impact sensor selection based on mass, power, and operability constraints are also discussed. The intent is to present challenges to facilitate alignment of new sensing solutions with key sensing requirements of planetary surface robotics.*

## Keywords

Planetary rovers, perception, space robotics, sensor design.

## INTRODUCTION

NASA employs autonomous mobile robotic vehicles (rovers), instrumented with a variety of sensors, as surrogate explorers on remote planetary surfaces such as the desolate and rocky terrain of Mars. The utility of autonomous rovers is a function of their ability to move about and explore intelligently without frequent contact with Earth-based mission operators. As such, rover autonomy and success of planetary surface missions is closely related to the rover's ability to *sense* and perceive its surrounding unstructured and uncharted environment. For outdoor mobile robotics applications, a variety of sensors are commonly employed to measure the presence of or range to obstacles, robot bearing and location with respect to the environment, and robot motions. The existing sensor types are as varied as the physical phenomena underlying their operation (e.g., optical, acoustic, inertial, magnetic). Despite the large variety of available sensor technologies, planetary rover sensor systems cannot readily take advantage of them due to limitations and/or constraints related to mass, volume, power, and operability/survivability in the space environment. To date, available sensor options have enabled limited success in our ability to produce intelligent autonomous robotic vehicles, despite major advances in computing technology and algorithms for autonomy. Indeed, computing is only part of the solution. New and improved sensing solutions are also required to advance to the next level.

The purpose of this paper is to highlight some of the sensing and perception issues facing the space robotics community, and to bring them to the attention of the sensor development community. We outline some of the challenging sensing problems for intelligent planetary rovers for which practical solutions from sensor developers would vastly improve rover capabilities, and enhance planetary surface mission success. Furthermore, we discuss some of the practical motivations for selecting certain sensors and rejecting others based on mass, power, and operability constraints (often non-issues for Earth-based robot applications). We describe sensors employed on planetary rovers to date, their primary utilities for rover mobility/navigation and manipulation, and functional sensor alternatives of limited use in planetary surface environments. Particular sensing capabilities needed to advance the state-of-the-art in planetary surface robotics are also discussed. Finally, the paper concludes with a brief summary.

## PLANETARY SURFACE ROBOTICS

Autonomous rovers designed for planetary surface exploration must be capable of navigation in the presence of varying surface obstacle distributions (rocks, boulders, etc.), surface characteristics, and hazards. Mobility and navigation hazards include extreme slopes, sand/dust-covered pits, ditches, cliffs and otherwise unstable surfaces. Rovers must avoid surface hazards and negotiate obstacles to be of practical use for carrying out the goals of scientific exploration in natural environments. Figure 1 shows an image of the Martian landscape where the Sojourner rover operated during the NASA Mars Pathfinder mission in 1997 [1]. To navigate successfully in such environments, rovers must be able to detect mobility hazards and assess terrain traversability. Additional problems to be addressed for navigation include maintaining knowledge of rover position and attitude on the terrain, and mapping the local environment and its prominent features or landmarks. Hence, sensing and perception capabilities for navigation are essential for missions requiring land reconnaissance or survey for the purpose of scientific exploration.

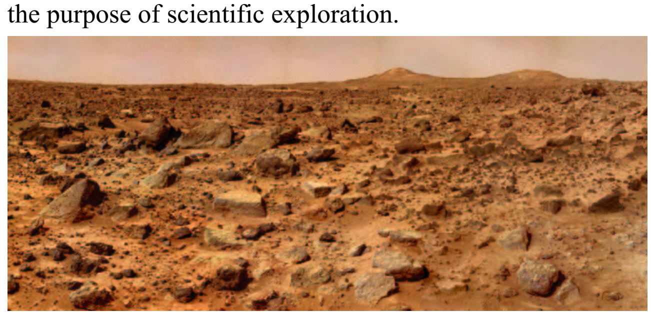

**Figure 1. NASA Mars Pathfinder landing site, 1997.**

Given the capability to perceive the environment and navigate successfully, rovers must be capable of carrying out particular scientific measurements, which may require manipulation of the environment. For example, if the objective of a science mission calls for acquisition of data or samples from the environment, a rover may require mechanized robotic appendages designed to grasp and manipulate (e.g., pick up or overturn) rocks, drill into rocks, dig into soils, or simply place sensors and instruments in contact with surface materials. In order to accomplish such manipulation tasks, rovers typically execute closed-loop feedback control of robotic arms/mechanisms, with the essential feedback provided by appropriate sensors. Further considerations for achieving reliable manipulation include avoiding collisions of the robotic arm with the rover itself and with the terrain [2, 3]. Oftentimes, it is also necessary to compensate for errors associated with degradations and/or changes in the manipulator hardware due to environmental factors such as spacecraft launch/landing vibrations and material thermal expansion, which can effect the ability to accurately position a rover-mounted manipulator at a target of interest [4]. Sensing for manipulation is essential for missions requiring sample acquisition and *in situ* scientific measurements.

Autonomous navigation and manipulation are fundamental functions for planetary surface robotics tasks. Viable sensing solutions that support these functions drive the technological capabilities of rovers, and ultimately, rover mission success.

## SENSING CONSTRAINTS & CHALLENGES

Candidate sensor suites for robust outdoor mobile vehicle navigation may include: stereo cameras for computer vision; laser, millimeter-wave, and/or ultrasonic rangefinding devices; MEMS-based inertial measurement systems; optical encoders; potentiometers; mechanical gyroscopes; magnetic compasses; etc. It is generally not very difficult to select sensors from among these types that satisfy requirements of outdoor robotics applications (barring cost as a constraint). However, the requirements for sensors that can be feasibly integrated on planetary rovers differ from those amenable to Earth-based robotics, thus adding a unique twist to an otherwise complicated problem.

In particular, sensor devices and systems employed by rovers must comply with certain specifications of rover size and payload capacity, onboard power availability, thermal limitations, and radiation hardness/tolerance. Such constraints are imposed by characteristics of the target space environment and mission objectives among other things, such as the rigors of space travel for example. Preferred solutions are mechanically simple, require low power and low mass, and are flight qualified [5]. That is sensor electronics (including associated embedded computing) should be qualified to survive and operate within the harsh temperature and radiation extremes of outer space, and on planet surfaces with thin atmospheres (such as Mars).

Constraints on sensor devices and systems are so-called *hard* constraints since reliability of space hardware is paramount (hardware repairs cannot be performed post-launch; not yet at least). For the reasons mentioned above, certain designs and configurations for sensor electronics and mechanical components are preferred for selection over others. For example, solid-state solutions for hazard detection sensor systems (e.g., passive stereo vision or active laser rangefinders) are preferred over mechanically scanned systems (e.g., laser scanners) [5]. Similarly, if mechanical components must be employed to actuate sensor devices, designs requiring few or no moving parts are preferred. Such components stand a better chance of surviving the vibration and gravity forces of spacecraft launch, atmospheric entry, and landing associated with flights from Earth to other planet surfaces.

Since science is the primary objective of planetary surface missions, significant percentages of rover power resources, mass, and volume are dedicated to onboard science instruments (versus navigation and manipulation sensors). The usual power source for rovers is solar energy absorbed by rover-mounted solar panels, although some designs and mission constraints permit the luxury of backup batteries that may be recharged via the solar panels. In either case, rover size governs its power budget since size determines the amount of surface area available for a solar panel as well as the payload capacity for carrying batteries. All onboard instruments, computers, and sensors utilize these power sources; so power must be efficiently distributed albeit with a modest allocation to sensors. Passive stereovision is preferred for rover navigation over some of the alternative active ranging sensors for such power related reasons. Since it is passive, sunlight provides the required energy for daylight operations. Hence, minimal power is required by the passive stereo electronics to serve the dual purpose of providing sensing for navigation and scientific knowledge of the environment through images [6]. Low power consumption by navigation and manipulation sensors makes way for increased science throughput; and sensor systems of low mass permit larger payloads for science instruments. In many rover design trades, multiple conflicting objectives abound, simultaneously requiring miniaturization, low mass and low power, for example [7]. As a result, sensing and perception system design for rovers is a challenging undertaking, and a fertile area for innovation by developers of sensor science and technology.

## LIMITED EARTH-BASED SOLUTIONS

In this section, we highlight some of the sensors commonly used for outdoor robotics applications on Earth that involve navigation problems of scope similar to that of planetary surface robotics. Examples of such Earth-based applications include: military land operations of reconnaissance, surveillance and target acquisition; search and rescue operations; and agricultural, construction, and mining automation. The sensors highlighted herein should be considered as examples, which support the fact that the set of viable sensors for rovers is a small subset of the many proven sensors for terrestrial outdoor robots. The set of examples mentioned is certainly not complete. Each sensor has limitations that preclude its effective use in the context of rover navigation. Earth-based outdoor robot applications that actually employ manipulators typically utilize vision-based perception, proximity sensors (based on infrared or electrical capacitance, for example) and force/torque sensors. By and large, this is also the case for planetary rover applications. Since there are not many significant sensing limitations that distinguish these applications, comparative sensing issues for manipulation are not addressed here.

### Navigation Sensors

In the context of navigation problems described above, a variety of ranging sensors have been successfully applied. A common realization for range sensors is based on time-of-flight measurement of acoustic waves. Ultrasonic rangefinders are quite common for indoor robotics applications and to a lesser degree outdoors. They are even less frequently proposed for planetary surface robots. While acoustic sensors will not operate in the vacuum of space, they can be applied on the surface of Mars if the mechanism responsible for generating acoustic waves is effective in its thin atmosphere. If so, additional care must be taken to account for the difference in the speed of sound in the Martian atmosphere (~95% carbon dioxide), which is a function of the ratio of specific heats, the gas constant, and temperature. A range sensor of similar popularity is the laser rangefinder. Laser ranging systems extract range information from an image scene, typically using one of two main techniques: active laser scanning and active triangulation [8]. We have already alluded to some drawbacks of mechanically scanned devices and active ranging sensors. However, they are worthy of discussion here since they are used often on Earth-based robots. For laser scanning systems, two types of laser are amplitude-modulated-continuous-wave lasers and time-of-flight lasers. The former are quite sensitive to natural light, which makes them unsuitable for outdoor environments. The latter perform well at long ranges and in outdoor environments, but have limited spatial resolution. Active laser scanning differs from active triangulation in that active triangulation methods utilize non-mechanical scanning systems. In this type of system, a stripe of light is projected onto the image scene, and a sensor extracts depth information from the associated projection. A structured-light implementation of this technique using 5 lasers was used for hazard detection by the Mars Pathfinder rover in 1997, and later improved using only 2 lasers [5]. Overall, laser scanners are useful for extracting range information in robotic applications but can be somewhat sensitive to environmental conditions, such as dust layers found on Mars, which effectively scatters the return pulse received by the laser system. However, recent signal processing algorithms have solved this problem [8].

A common sensor for position estimation and localization is the satellite-based Global Positioning System (GPS), which provides accurate outdoor position knowledge in terrain where sufficient reception can be achieved. Of course, there is no existing analogue available for global positioning at Mars, and this is a major limiting factor of localization accuracy achievement for rover systems. It should be noted that potential viable solutions are on the horizon. Namely, studies and plans are underway to establish a telecommunications network infrastructure at Mars called the Mars Network [9]. One of the primary functions of the proposed network of satellites would be to provide enhanced navigation support for surface rovers. A less elaborate solution has also been proposed which is based on ground-based GPS-type transmitters called pseudolites (pseudo-satellites) [10]. This technology would allow use of GPS-type positioning in a local area using the recently developed concept of self-calibrating pseudolite arrays. The individual devices must first be physically placed at distributed locations in the local area (perhaps a task for the rover itself). The array permits pseudolites to determine their own position on the surface relative to the each other with centimeter-level accuracy. Accurate knowledge of pseudolite positions enables accurate rover localization in the local area. The pseudolite approach could also be used to achieve higher local accuracy than potentially possible with the proposed Mars Network.

In addition to maintenance of accurate position estimates, robust navigation requires accurate heading measurement or very good heading estimation. Errors in heading estimates directly affect the accuracy of rover position estimates. Optical encoders, potentiometers, or revolvers are often used to measure revolutions of robot wheels. Such measurements allow heading and position estimation via dead reckoning or wheel odometry (based on the robot kinematics) relative to some known starting position and heading. However, in rough and rugged outdoor terrain these estimates are only reliable over short distances. Thus, for long-range traverses more reliable heading information is required. To achieve this, Earth-based robots often employ magnetic devices, such as compasses, which provide good absolute heading measurements with respect to true north of Earth's magnetic field. Magnetic heading sensors are not as useful on Mars, however, due to the planet's negligible magnetic field.

## PLANETARY ROVER SENSING

In this section, we briefly describe a viable sensor suite that is representative of those selected for state-of-the-art rover prototypes and actual space-bound (flight) rovers. As a representative rover example, we use the Field Integrated Design & Operations (FIDO) rover (see Figure 2) designed, built, and operated by NASA/JPL [11]. The FIDO rover represents a central integration platform for the development, rapid prototyping, and testing of advanced Mars robotics technologies on Earth. It is not a flight rover that will actually be flown to Mars, but it is a fully functional prototype for the flight rovers being developed for the Mars rover mission to be launched in 2003 by NASA. This rover is designed to accomplish the objectives of near-term Mars missions, and has proven useful to the Mars science community for high-fidelity mission concept testing, validation, and physical mission simulation via annual terrestrial field trials [12].

The FIDO rover is equipped with navigation sensors including front and rear passive stereo vision for local hazard detection and avoidance, as well as stereo cameras mounted on a mast that can be extended up to 2 meters above ground using a manipulator mounted at its rear. The rover also uses an Inertial Measurement Unit consisting of a 3-axis accelerometer and a 3-axis gyroscope. Its MEMS accelerometers are used for measuring the local gravity vector (i.e., which way is down?). This provides rover tilt/attitude measurements, which are useful for maintaining upright stability to avoid tip-over, and for measuring rover heading (yaw). The gyroscope measures angular rates of change of the vehicle. A CCD-based sun sensor is also included, which provides absolute heading measurements relative to true north [13]. These sensors, along with encoder-based wheel odometry, contribute to a fused estimate of position and heading via Extended Kalman Filtering.

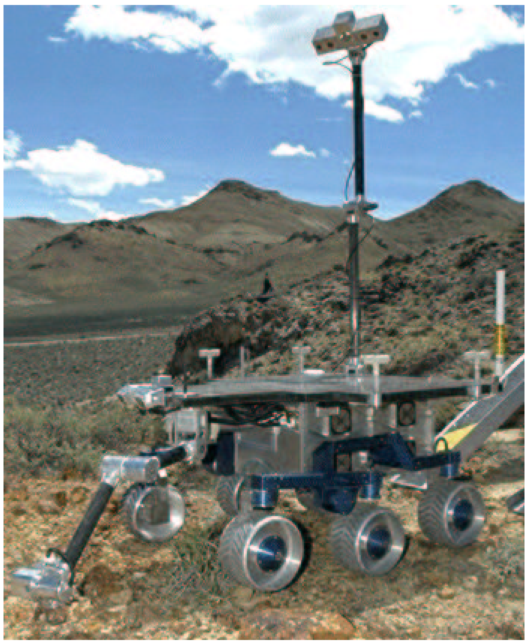

**Figure 2. JPL's FIDO Rover.**

FIDO includes an additional set of stereo cameras mounted in the frontal area beneath its solar panel. This stereo pair is used to view the workspace of an onboard core drill mounted in the same area. Core drill motors are controlled using encoder feedback. In addition, a manipulator arm is mounted to the front of the vehicle and is outfitted with instruments at its end-effector. The core drill and instrument arm end-effector utilize contact/force sensors to facilitate controlled interaction with rocks and soil. The front hazard cameras are also used to view the workspace of the instrument arm and facilitate avoidance of collisions with the terrain and rover. Both the rover mast and instrument arms utilize potentiometers and encoders for joint position and feedback for motor control of manipulator joints. Finally, the various articulations of the mechanical mobility system are measured using potentiometers. Besides sensors used for mobility/navigation and manipulation, the FIDO rover also includes a number of science instruments not included in the scope of this paper. It should be noted, however, that instruments for planetary rovers often have integrated sensors to facilitate their functionality as well. The rover is a self-contained system powered by a solar panel or batteries, and requires less than 25 watts of power. More information is available on the World Wide Web at http://fido.jpl.nasa.gov.

This representative suite of sensors enables safe and reliable natural terrain mobility, autonomous navigation, and autonomous sensor-based manipulation capabilities suitable for planetary surface robotics. Several limitations remain which may be overcome by innovations and advances in sensing and perception. We elaborate on some of the limitations below to highlight particular sensing needs.

## NEEDS FOR ADVANCED SENSING & PERCEPTION CAPABILITY

In order for planetary surface robotic systems to advance to the next level of autonomous capability, new and improved sensing solutions are required. Stereo machine vision should be mentioned in this context since advances are required to reduce the computational complexity of related algorithms, or to increase the computational speed of radiation-hardened processors. For the purposes of this paper, we consider this more of a computing issue than a sensing issue, so we will not elaborate further here. For recent insight into the state-of-the-art for dealing with rover stereo image processing complexity see [6]. Some sensing and perception capabilities for which existing rover systems have limited solutions include:

- detection or measurement of significant wheel-terrain interactions such as slippage and sinkage,
- assessment or measurement of certain terrain properties prior to engagement by the rover.

We will now discuss some interesting aspects of these sensing problems to provide background meant to motivate further study that will lead the sensor technology community to viable solutions.

### Wheel Slip

Wheeled mobility systems are subject to undesirable wheel-terrain interactions that cause wheels to slip on rocks and soil. Loss of traction due to excessive wheel slippage can lead to wheel sinkage and ultimately vehicle entrapment. Frequent loss of traction due to wheel slip during traverses from one place to another will also detract significantly from the ability to maintain good rover position estimates. This makes it difficult to localize the rover in its environment. It is highly desirable to have a capability to sense wheel slippage so that corrective control actions may be taken. Barring direct measurement of wheel slip, measurement of over-the-ground rover speed would allow calculation of percentage slip using a well-known analytical relationship between slip, over-the-ground speed, and wheel linear speed (as derived from encoder readings or tachometers, for example). The problem here is that true over-the-ground speed is also difficult to measure. For example, if a rover attempts to drive forward while all wheels are slipping, interpretation of wheel encoder readings alone will indicate forward progress; but in all probability the rover position will not have changed significantly.

As mentioned above, existing rover sensor suites typically include accelerometers for measuring the local gravity vector. In principle, accelerometer measurements could be integrated to derive rover velocity as well. In practice, however, the use of an accelerometer for this purpose is problematic since the gravity effects of traversing longitudinal and lateral slopes of natural terrain will interfere with the measurement. For an accelerometer used to measure horizontal acceleration, any off-horizontal vehicle tilt will be sensed as a change in acceleration; as a result, the integrated velocity will be in error. Some Doppler and millimeter-wave radar solutions exist for measuring true vehicle speed but for rover use, they must be low-power and low-mass devices.

### Wheel Sinkage

Undesirable wheel-terrain interactions also can cause wheels to sink in soft soils. It is possible for wheels to sink to soil depths sufficient to prohibit rover progress over terrain, thus trapping the vehicle at one location. Like wheel slip, it is desirable to have a capability to sense excessive wheel sinkage so that corrective controls may be executed before immobility results. Sinkage measurements are also valuable for reducing position estimation errors. As the load-bearing strength of terrain/soil varies under rover wheels, so does the amount of wheel sinkage. This has the effect of varying the effective radius of the rover wheels. The accuracy of kinematic models used to compute rover position updates depends on accurate knowledge of wheel radius, which is used to compute the equivalent linear distance traveled by a wheel after some measured rotational displacement on the terrain. For compliant wheels/tires the effective wheel radius is reduced as the tire compresses in normal reaction with the terrain. Rigid or non-compliant wheels (such as those on the FIDO rover) produce a similar effect. For example, as a vehicle with non-compliant wheels traverses terrain with both hard-packed soil and soft sand, use of the nominal wheel radius to compute position updates is valid only over the hard-packed terrain. As the terrain load-bearing strength decreases (over softer soil), so does the effective wheel radius, and the accuracy of the model. To reduce the effect of propagating this non-systematic error during rover traverses on varied terrain, a means to measure wheel sinkage (and therefore effective wheel radius) is needed.

### Terrain Properties

Capabilities for non-contact sensing of terrain properties such as hardness or bearing strength are needed for detecting mobility hazards. The passive stereo or other ranging systems available on existing rovers cannot detect pits filled with loose drift material that may have insufficient load-bearing strength to support a rover. Such hazards are known to exist on the Martian surface [14] and need to be detected before a rover engages them, only to meet with catastrophe. Downward-looking impulse radar has been suggested as a proximity sensor for this problem [15]. Similar millimeter-wave and microwave ranging sensors are useful for general outdoor collision avoidance in environments subject to dust, blowing sand, and other all-weather conditions [16, 17]. However, the mass of available units may be prohibitive for some planetary rover applications, and like the speed measurement radars mentioned above, candidate radars for terrain property sensing must be low-power and low-mass devices.

### Additional Sensing Needs

Presently, devices for sensing or detecting wheel slip, wheel sinkage, and terrain hardness are among the greatest sensing needs for planetary surface robotics. There also are strong desires for viable devices that can improve existing capabilities for:

- sensing large-scale terrain discontinuities such as cliffs, craters, and escarpments;
- optical ranging in both full sun and deep shadow;
- distributed sensing in multiple-rover applications.

## SUMMARY

In summary, planetary surface robotics requires mobility, navigation, and manipulation functionality. To achieve successful rover missions, each function must be supported by viable and adequate sensing and perception solutions. In contrast to many Earth-based outdoor mobile robot applications, sensor devices and systems employed by planetary rovers must comply with hard constraints on mass, power, mechanical complexity, and electrical characteristics. Commonly employed sensing solutions for Earth-based robots are of limited use in other planetary surface environments due to these constraints, as well as to environment extremes and lack of supporting infrastructure (e.g., in the case of GPS). Furthermore, existing solutions for planetary rover sensing and perception require improvements or replacement with new solutions that enhance rover capabilities. Some of the greatest needs in this regard are discussed.

This expository paper points out some of the major challenges of rover sensing and perception. Several remaining limitations are also highlighted, which may be overcome by innovations and advances in sensing and perception. The paper is meant to facilitate alignment of new sensing solutions with key sensing requirements and the present needs of space robotics systems.

## ACKNOWLEDGMENTS

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