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PLANETARY ROVER TECHNOLOGY DEVELOPMENT REQUIREMENTS

Roger J. Bedard Jr. and Brian K. Muirhead
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109
and
Dr. Melvin D. Montemerlo and Murray S. Hirschbein
National Aeronautics and Space Administration
Office of Aeronautics and Space Technology
Washington D.C. 20546

ABSTRACT

Planetary surface (including lunar) mobility and sampling capability is required to support proposed future National Aeronautics and Space Administration (NASA) solar system exploration missions.

The NASA Office of Aeronautics and Space Technology (OAST) is addressing some of these technology needs in its base research and development program, the Civil Space Technology Initiative (CSTI) and a new technology initiative entitled "Pathfinder". The Pathfinder Planetary Rover (PPR) and Sample Acquisition, Analysis and Preservation (SAAP) programs will develop and validate the technologies needed to enable both robotic and piloted rovers on various planetary surfaces.

This paper discusses the technology requirements for a planetary roving vehicle and the development plans of the PPR and SAAP programs.

1. INTRODUCTION

A planetary surface (including lunar) mobility and sampling capability is required to support proposed future National Aeronautics and Space Administration (NASA) solar system exploration missions.

The Mars Rover Sample Return (MRSR) project is the earliest NASA project identified as needing planetary rover mobility and sample return technology. MRSR is currently targeted for a late 1990's launch. The value of planetary landers in surveying future landing sites for manned missions was demonstrated by the Surveyor lunar missions. The value of planetary landers in performing scientific exploration was demonstrated by the Surveyor and the Viking Mars mission. Surveyor and Viking collected scientific data within local areas about the landing sites. In many cases, however, areas of scientific interest are likely to be in regions remote from acceptable safe spacecraft landing sites.

Manned and unmanned rover technology to support exploration, mining and construction are required for the crewed Lunar and Mars missions.

The NASA Office of Aeronautics and Space Technology (OAST) is addressing some of these technology needs in its base research and development program, the Civil Space Technology Initiative (CSTI) and a new technology initiative entitled "Pathfinder". The Pathfinder Planetary Rover (PPR) and Sample Acquisition, Analysis and Preservation (SAAP) programs will develop and validate the technologies needed to enable scientific and exploration missions by robotic and piloted rovers on various planetary surfaces. In its first phase, the program will be focused on automated, unmanned rover technologies needed for a Mars rover sample return type mission.

The eventual need for autonomous navigation, autonomous sample acquisition, robust mobility, low mass electrical power, fault tolerant computing, high bandwidth communications and mission operations autonomy are enabling technologies which affect the vehicle's travel range and science return. The implementation of these requirements forces advances in several areas of technology; namely:

o Mobility,
o Navigation,
o Sample Acquisition, Analysis and Preservation,
o Mission Operations,
o Computation,
o Power,
o Temperature Control,
o Communication.

Development and integration of these technologies will allow orders of magnitude increase in the effectiveness of remote surface operations.

2. MOBILITY

A mobility system must combine locomotion, stability and ruggedness over a wide variety of terrains with acceptable power consumption and reasonable control requirements. A number of experimental locomotion concepts which appear suitable for planetary surface operations have been built and tested. These concepts encompass wheeled, legged and hybrid configurations.

The state-of-the-art is:

o Wheeled locomotion with moderate mobility characteristics,
o Three dimensional (3-D) vehicle / terrain modeling for higher speeds (commercial and military vehicles) than those of interest,
o Lunar rover wheel packaging and deployment concepts.

The mobility technology needs include:

o A practical, high mobility locomotion system with low mass and power consumption and automated control capability (reasonable control requirements),
o A general modeling capability for vehicle / terrain obstacle climbing is needed for comparative assessment of locomotion options, vehicle dynamics and control verification and expectation generation/execution monitoring,
o Deployable locomotion structure concepts / technologies that offer efficient packaging of the vehicle within the volume constraints of the aeroshell,

- o Adaptable locomotion structure concepts / technologies that allow flexibility in response to different terrain and rover operational states.

3. NAVIGATION

Because of the long signal time to Mars (6-44 minutes round trip), it is impractical to continuously teleoperate a Martian Rover from Earth (one on which individual movements are controlled from Earth). Therefore, some navigation autonomy on the Rover is needed. A highly autonomous rover capable of traveling safely over long distances for many days in unfamiliar terrain without guidance from Earth is well beyond the present state-of-the-art. In between the extremes of continuous teleoperation and highly autonomous, various degrees of autonomy are possible. Two in particular; namely, computer aided remote driving (CARD) and semiautonomous navigation (SAN) have been identified as feasible with additional technology development.

With CARD, stereo pictures from the rover are sent to Earth where they are viewed by a human operator using a stereo display. The operator designates a safe path for the vehicle to follow as far ahead as can be seen. This plan is sent to the rover which executes the path by dead reckoning navigation aided by computer vision. A new stereo pair of pictures is taken from the new position and the process repeats itself. Depending on the terrain, the rover might travel 5-30 meters on each of these iterations. Assuming 2-7 command cycles from earth per day, the daily traverse would be 10-200 meters.

In the SAN method, local paths are planned autonomously (without interaction from humans on Earth) using images obtained on the vehicle, but they are guided by global routes planned less frequently by humans on Earth. These global routes are developed from a topographic map produced from images obtained by an orbiting satellite.

The sequence of operations, in the portion of SAN involving Earth, is as follows. As commanded from Earth, the orbiter takes a stereo pair of pictures (by taking the two pictures at different points in the orbit) of an area to be traversed. A spatial resolution of about 1 meter is desired. The pictures are sent to Earth where they are used by a human to plan an approximate route for the vehicle to follow designed to avoid large obstacles, dangerous areas and dead-ends. This route and a topographic map for the surrounding area are sent from Earth to the rover. The process repeats, as needed; perhaps once for each traverse between major sites where experiments are to be done, or perhaps once per day or so on long traverses.

The sequence of operations, in the portion of SAN taking place on Mars, is as follows. The rover views the local scene and, by using automatic stereo correlation or laser ranging, computes a local topographic map. This map is matched to the portion of the global map sent from earth for purposes of position determination. The high resolution local map is analyzed by computation on the rover to determine the safe areas over which to drive. A new plan is then computed, revising the approximate route from the Earth. Using the revised path, the rover then drives ahead a short distance (perhaps 5-10 meters), and then the process repeats. With SAN operation, a daily travel of 700-7000 meters is feasible.

The state-of-the-art permits rudimentary demonstration of CARD and SAN technology (no proximity contact sensing, surface property determination, expectation generation, execution monitoring, etc).

The navigation technology needs include:

- o World sensing and perception accomplished via multiple sensor and algorithm fusion weighted by certainty, time and sensor source,
- o Surface property determination via correlation of contact and non-contact sensor data and algorithmic / heuristic driven responses to results,
- o Robust path planning using multiple models and degraded terrain knowledge bases,
- o Expectation generation and execution monitoring and replanning for dynamic response to uncertainty in sensing and perceptual data.

4. MISSION OPERATIONS

The U.S. has operated a roving vehicle on the surface of another planetary body (the moon) with the direct involvement of a human driver (Apollo Program) and has operated an unmanned stationary lander on the surface of Mars (Viking). The U.S.S.R. has operated an unmanned roving vehicle on the surface of the moon (Lunakod). The operation of an autonomous unmanned rover on the surface of planet tens of light minutes away, however, represents an entirely unproven technology. In addition, the operations of the various rover subsystems (mobility, navigation, power, sampling, communication, etc) are highly interdependent and quite complex; thus providing a significant system operation challenge.

In order to maximize mission effectiveness, a high level of both onboard and ground based autonomy is essential.

The state-of-the-art is represented by Galileo uplink command generation technology which is oriented towards repetitive tasks and / or one-time tasks of short duration and Galileo onboard autonomy consisting of a few isolated autonomous low level subsystems.

The ground operations technology needs include an uplink command generation of non-repetitive, long-duration tasks with a couple orders of magnitude improvement in present command cycle turnaround times.

The onboard operations technology needs include the processing of high level goals at the system level.

5. COMPUTATION

JPL experience in past spacecraft projects and the premise for future projects is that mission capabilities are limited by the performance of onboard computers. Thus it is essential to maximize the computer capability for future spacecraft missions.

Unmanned rover computation requirements include general purpose and special purpose processing, fault tolerance, fast processing speed, low power consumption, low mass, space qualified computers organized in a distributed, parallel processing architecture. High speed, high capacity data storage is also required.

The state-of-the-art is represented by the Mariner Mark II (MM II) flight computer (32032 processors with 0.25 million instructions per second (MIPS)/processor, 20 watts/MIPS and 300 components/processor) and digital tape recorder (sequential access) technology.

The computation technology needs include:

- o 5-10 MIPS general purpose computer with 1-4 MIPS/processor, 4-8 watts/MIPs and 50-100 components/processor,
- o 200 MIPS (or equivalent) special purpose image processor,
- o High performance, nonvolatile, random access data storage.

6. POWER

A planetary requires a compact, lightweight, very high capacity onboard power system. A Radioisotope Thermal Generator (RTG) is the preferred heat source for the power levels required for an unmanned rover vehicle (ie, about 500 - 1000 watts). Advanced thermoelectric multicouples provide the thermal to electric energy conversion. Advanced sodium sulfide or lithium titanium disulfide batteries supplement the RTGs during periods when increased power is required for higher speeds, obstacles or increased slopes. Reduced mass / volume power conditioning / control integrated circuit elements are also required.

The state-of-the-art is represented by:

- o Galileo RTGs, with a specific power of 5 W/Kg, are designed for operation in the vacuum of space; there is no existing power source / conversion technology capable of operating in an atmosphere (Viking RTGs, although not available today, had a specific power of about 2 W/Kg),
- o Current energy storage technology (nickel hydrogen batteries) provides a specific energy of 45 Whr/kg,
- o Galileo power conditioning / control elements (discrete components) provide a specific power of 12 W/kg and a power density of 0.06 W/cm^3.

The power technology needs include:

- o A planetary surface RTG energy source and thermal to electric conversion system with a specific power of 10 W/kg,
- o Increase the specific energy of storage components (to 100 Whr/kg),
- o Increase specific power and power density of conditioning / control elements (to 21 W/kg and to 0.5 W/cm^3).

7. TEMPERATURE CONTROL

A planetary rover requires an efficient thermal transfer and control system for maintaining rover elements within temperature limits for all environmental exposures from pre-launch through surface operation. Thermal energy storage may be required during aerocapture or during high power dissipation or adverse environmental conditions.

The state-of-the-art is represented by conventional spacecraft two phase thermal control materials and devices.

The planetary rover thermal control technology needs include the development of two phase heat transfer loop technology for application to planetary surface operation (gravity, atmosphere, dynamics, etc.) and higher efficiency temperature control materials that operate in a hostile planetary atmosphere.

8. COMMUNICATIONS

A Ka-band (32 GHz) communication downlink (from Mars to Earth) offers significant advantages compared to existing X-band (8.4 GHz) technology. These advantages include higher data rate, greater link reliability, smaller antenna size (important for packaging in the aeroshell) and increased availability (X-band communications from Mars would require the 70 meter Deep Space Network (DSN) stations with a forecasted availability of 30% in the late 1990's as compared to the forecasted 100% availability using Ka-band and the 34 meter DSN stations).

The state-of-the-art is:

- o Laboratory demonstrations of small monolithic millimeter arrays,
- o X-band solid state and traveling wave tube (TWT) amplifier,
- o Ka-band TWT efficiency of about 20%,
- o Commercial Ka-band field effect transistors (FET) power of about 0.15 W.

The communication technology needs include:

- o A Ka-band monolithic transmitter phased array with over 100 elements producing 40 W of output power and greater than 30% overall DC to RF conversion efficiency,
- o Millimeter wave integrated circuit (MMIC) digital data phased array signal distribution system,
- o High DC to RF conversion efficiency MMIC (40%) and TWT amplifiers (45%) operating at 32 GHz.

9. SAMPLE ACQUISITION, ANALYSIS AND PRESERVATION

The primary function of an unmanned or piloted rover in any planetary exploration mission is to provide the mobility to enable exploration and to conduct scientific surveys. The technology developed under the SAAP program is intended to be carried by a rover as part of science and exploration missions, and as such, the SAAP and PPR programs must be well coordinated.

The rover must have the ability to identify promising sites which contain scientifically interesting surface samples. It then must have the ability to acquire the desired samples. This will require imaging and ranging instrumentation to provide multi-spectral data for precise sample location and a robotic system to acquire the samples. Once acquired, analytical equipment onboard the rover will determine the sample's elemental, chemical and physical properties in order to determine which samples to keep. The selected samples must then be preserved in a pristine condition for return to the ascent and Earth return vehicles.

Sample acquisition, analysis and preservation are enabling technologies which effect the science and exploration value of an autonomous rover. Similar to the two types of rover navigation scenarios, SAAP technology falls within two bounding cases. In one, operators on Earth retain full control. All directives concerning sample selection, acquisition and analysis are controlled from Earth. In the other, the more ambitious scenario, these functions are performed autonomously based on planning and decision criteria formulated on Earth prior to the mission. During the mission, Earth operators interact with the system in a supervisory manner.

In developing SAAP technology, it will be important to determine the extent to which autonomous operations can be used to augment Earth-based control. SAAP systems will be operating in unfamiliar environments which can only be approximated on Earth. While there is significant reluctance among the scientific community to lessen Earth-based control of SAAP operations, it is recognized that much more science can be accomplished if more planning and decision making responsibility can be initially assigned or later delegated to the SAAP system.

The state-of-the-art is represented by Viking lander sample acquisition and analysis technology and Apollo / Space Shuttle biomedical freezer sample preservation technology. The Viking sample acquisition system was basically a scoop, with a movable lid and a backhoe hinged to its lower surface, attached to the end of a retractable boom. The analytical instruments included a x-ray fluorescence spectrometer, a gas chromograph-mass spectrometer and a biology package.

Lunar samples returned to Earth in the Apollo program were not temperature controlled as will be required for Martian samples. Thermally controlled container technology, however, has been developed for biomedical experiments aboard the Space Shuttle.

The sample acquisition, analysis and preservation technology needs include:

- o High speed broadband multispectral data acquisition and analysis
- o Lightweight, low power manipulator(s), end effector(s) and tools with associated control system,
- o Autonomous core drilling,
- o Lightweight, low power analytical instruments and technology for elemental, chemical and physical property determination, and onboard analysis and decision making.
- o Sample preparation technology to process samples for analysis and/or storage,
- o Sample preservation technology including environmental control of samples (most importantly lowest mean annual temperature of about -40 degrees C) during in-situ analysis and for the duration of the mission.

10. PATHFINDER PLANETARY ROVER AND SAMPLE ACQUISITION, ANALYSIS AND PRESERVATION DEVELOPMENT PLANS

The Pathfinder Planetary Rover and Sample Acquisition, Analysis and Preservation programs are multi-year, focused development programs which will validate automated and piloted rover technological maturity sufficient for use by prudent project managers. The initial focus is on automated unmanned rover technology for exploration and science. Later needs are for rover systems for automated construction and mining and for exploration with human driven rovers.

The PPR program includes three major work element types; namely:

- o Advanced development of unmanned planetary rover subsystem technology,
- o An integrated unmanned planetary rover testbed,

- o Advanced development of piloted rover technology for exploration and automated rover technology for mining and construction.

Advanced unmanned planetary rover subsystem technology development encompasses seven work items; namely, mobility, navigation, ground operations, computation, power, temperature control and communications. The SAAP program will develop the subsystem technology required to identify, acquire, analyze and return to Earth scientifically valuable specimens from a planets surface or near subsurface. The technology requirements delineated in sections 2 through 9 will be achieved, in a phased manner, within a five (5) year time frame.

An integrated testbed will be defined, implemented and operated. This testbed will provide a focus for and a means of validating the advanced subsystem technology as well as the integration technology and will serve as a mechanism for the technology transfer process. The definition phase will be completed in FY 90. The initial testbed implementation will be completed in FY 92.

Piloted rover and automated mining/construction rover technology work elements are planned for initiation in the FY 91 time period. Detailed planning of these work elements has not yet been performed.

NASA responsibility for the PPR program rests with the Information Sciences and Human Factors Division of OAST. NASA responsibility for the SAAP program rests with the Materials and Structures Division of OAST. JPL has coordination and management responsibility for the implementation of both the PPR and SAAP programs. Other NASA centers involved or to be involved in the program include the Ames, Lewis and Langley Research Centers and Johnson Space Center. Universities will have an important role in the PPR program as well. Carnegie Mellon University (CMU) is developing an innovative legged locomotion mobility prototype vehicle with its associated sensing, perception, planning and reasoning systems. Industry will also play an important role in the PPR program; initially in the component development area and later, in the implementation and operation of the integrated testbed.

11. SUMMARY

Planetary rover technology advances are needed in the areas of mobility, navigation, sample acquisition, analysis and preservation, mission operations, computation, power, temperature control and communication technologies. The NASA Office of Aeronautics and Space Technology (OAST) is addressing these technology needs in its base research and development program, the Civil Space Technology Initiative (CSTI) and a new technology initiative entitled "Pathfinder". The Pathfinder Planetary Rover and sample Acquisition, Analysis and Preservation programs will develop and validate the technologies needed for both robotic and piloted exploration of various planetary surfaces. Pathfinder does not represent, in itself, a commitment to any particular mission. It will, however, provide a variety of high-leverage technologies which will help enable future national decisions regarding exploration of the Solar System.

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