“Robotics Technology for Planetary Missions Into the 21st Century”

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1. INTRODUCTION

This paper summarizes the objectives, current status and future thrusts of technology development in planetary robotics at the Jet Propulsion Laboratory, under sponsorship by the NASA Office of Space Science. The major overarching goal of this thrust is to enable exciting in-situ exploration missions to planets, comets, and asteroids currently in planning by NASA into the 21st Century. This is done in support of the Space Science quests [1] to understand the origin of life, its existence beyond earth, the evolution of earth-like planets, and the suitability of planetary exploration by future human missions.

Robotic systems under development include:

- Long range science rovers (20-50 kg mass) which enable 50-100 km traverse in 1-2 years in support of Mars rover sample selection and sample return missions on a timeline consistent with Mars Exploration mission plans (e.g. 2001, 2003 missions).
- Lightweight fast moving rovers, based on composites, that can quickly acquire a cache of material for return to the ascent vehicle, secure containerization, and provide for planetary quarantine (e.g Mars 2005 sample return mission).
- Lightweight, long-reach, stowable, planetary robotic arms; microarms that are able to chip and core rocks to get beneath weathering rind; sampling end-effecters to acquire and handle scientific samples (-10-20 gm) from landers and rovers (e.g Mars 2003 mission); as well as for robotic anchoring and drilling devices for missions to primitive bodies (ice, rocks, regolith).
- 10-200 gm nanorovers, which fit within the residual contingency of mission mass, and can act as special-purpose machines for in-situ, localized surface exploration. First mission

Technologies Needed To Enable Rover Functions

Function Required	Technology Required
Survivability - Survive on the surface of Mars for up to 2 years	Methods for identification of critical failure modes of the rover, including both damage accumulation modes and operational modes, Rotrust synthesis of technologies in thermal control, low-temperature batteries, fault-tolerant robot software, etc.
Long Distance Traverse - Rove up (o 100 km total traverse in Viking 2 terrain	Long distance navigation and hazard avoidance system
Cache Samples - Find and return sample package prepared in a previous mission	Rover-based sample selection, acquisition & packaging system
Scaleable Architecture - Provide alternative technological options to mission design studies	Modular, rapid-prototyping vehicle hardware & software design approaches
Payload Mass Fraction - up to 50 % if possible, subject to achieving the four functional requirements above	Lightweight, collapsible structures; integrated vehicle/payload structure design methods

application may be for small bodies (-100 meters range).

- Miniature subsurface explorers, with integrated sensors, which can move to a depth of 0.5-1,0 m in the Mars subsurface or through primitive bodies, and analyze' soil composition; longer term development of sub-surface exploration techniques to depths of tens and hundreds of meters for both lander-based and roving systems. Vehicles for penetrating ice layers (10Om -10,000 m e.g. in Europa) and moving through potential underground bodies of water.
- Aerobots that: Enable sub-orbital mapping of terrain regions; can transport and deploy microrovers at different, geographically separate land sites; and which are under development for potential Mars, Venus and Titan deep atmosphere missions.

2. SURFACE MOBILITY AND SAMPLING

2.1 Perceived Needs and Status

A key set of rover and lander requirements emerge from NASA's thrust in Mars exploration [2-6]. The baseline mission is Mars Pathfinder, launched in late 1996 with a small rover named Sojourner (see Figure 1).

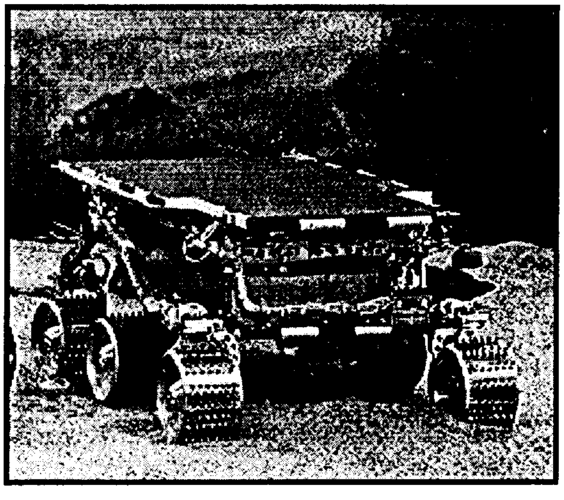

Figure 1- The Sojourner Rover, a Key Element of the Mars Pathfinder Mission

Long-range and lightweight rovers under development by the NASA Telerobotics Program are being evaluated for the Mars 2001 mission and beyond, with the search for water [3] and signs of life being among the primary objectives. Roving capability is essential for the 2001 mission to demonstrate the ability to navigate long distances and acquire interesting samples. In the emerging horizon are missions that will return samples [5] of Martian rocks and soil to Earth. This approach has been very successful in infusing telerobotics technologies into flight systems. Approval of the Sojourner rover for the Mars Pathfinder mission launched in December 1996, and to arrive at Mars in July 1997, is an early indication of the success of this approach. A robotic arm payload for lander-based science acquisition and handling has been approved for flight in the Mars Volatile and Climate Surveyor mission to be launched in 1998.

Figure 2- Advanced MicroRovers Undergoing Testing in Simulated Mars Landscape

A few functions have been identified by prominent Mars scientists [2,3] to be of the highest priority in order ensure the success of Mars rover missions in the first decade of the 21st Century. Table 1 provides a summary.

Table 1. Mars Mission Needs With NASA Technology Baseline and Requirements

Desired Capabilities	State of the Art	‘i’ethnology Requirements	Rover	Lander
Local surface mobility	Mars Pathfinder rover (Sojourner), 10kg	Rover scalable designs (<8kg; ≤ 50 kg)	X	
Long-range surface mobility (50-100 km)	Pathfinder-class, lander-based local navigation (30-m nominal mission)	Navigation systems with long-range position determination and path control	X	
Long operating life (100-1,000 days)	7-day nominal Sojourner mission	Thermal enclosures made of phase-change materials; thermal regulation systems 10 keep electronics and batteries warm	X	X
Sample acquisition and handling; sample-return processing and packaging	Mars Viking lander arm; MVACS long-reach arm prototype (3 m)	Lightweight systems with vision and touch-guided grasping; power-use management; and contact control	X	X
Subsurface sampling	Scraping and digging with MVACS arm	Subsurface mobile systems capable of ≥ 1-m penetration in Mars’ regolith;	X	X
Emplacing science instruments	Sojourner emplacement of a single spectrometer instrument (Alpha-Proton, X-Ray Spectrometer) in lander proximity	Systems for emplacement of multiple instruments at several sites visited in sequence	X	
Increased coverage per command cycle	Low-level command functions	Autonomy of 10-100 concatenated commands with online verification	X	
Terrain visualization and task planning	Imaging/sensing via points overlaid on raw images, 1 overlay per day	Imaging/sensing with onboard sensors and algorithms for creation of 3D fly-over models of terrain	X	
Surface hazard avoidance	Sojourner laser-stripe sensor and software	Stereo-image-based hazard sensing and processing	X	
Autonomous sample selection/science goal identification	Laboratory prototypes of goal-recognition systems	System capable of terrain-image analysis and object identification	X	

2.2 Some of the Activities of the Current Technology Program to Address These Needs

2.2.1 Microrovers and Rover Field Testing

2.2.1.1 Rocky 7 Field Experiments

A prototype of NASA’s next generation of Martian rovers, designated Rocky 7, has navigated successfully over a corner of Lavic Lake, an ancient lake bed about 175 miles east of Los Angeles, taking panoramic photographs and close-ups of the cratered terrain (Figure 3). The three-day experiment, conducted Dec. 17-19, 1996 by a team of engineers at NASA’s Jet Propulsion Laboratory led by Dr. Samad Hayati [7], was designed to demonstrate the rover’s ability to drive a much greater distance than current microrovers over rugged terrain with key features similar to those of Mars. The tests also demonstrated new mechanical innovations for 21st century rovers, such as: a robotic arm that would be used to dig into soil; and an agile mast that could be used to image the surrounding terrain and position miniature science instruments in tricky locations. The rover was very successful in making a long journey on its own, driving more than 200 meters (655 feet) to its target and relying on only specified location points along the way and information about the location of the target. The Rocky 7 experiment team working with Hayati included scientists and engineers from NASA’s Ames Research Center in Mountain View, Calif., Washington University in St. Louis, Me., Cornell University, Ithaca, N. Y., and scientific institutions abroad.

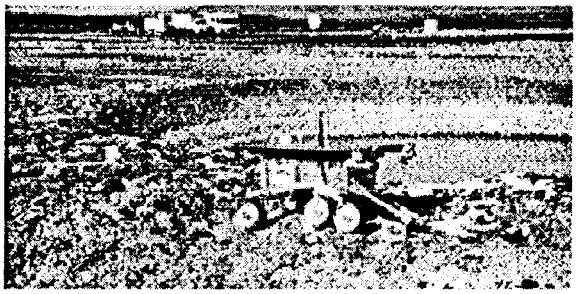

Figure 3- Rocky 7 Terrestrial Mars-Analog Field Experiments

2.2.1.2 Sample Retrieval Rover

The emphasis of the Sample Retrieval Rover task, led by Dr. P. S. Schenker[9], is on the development of lightweight, low volume, thermally robust, and computationally efficient designs, so as to optimize use of Mars science mass/volume/power resources in future missions. Current emphasis by the team is to create a sample retrieval rover (SRR): a new - 8 kg class vehicle (including 3 kg of combined payload and cache handling mechanization) that travels quickly to cached samples not much greater than 100 meters away, and returns them for ascent vehicle processing. Enabling technology development includes reduced stowage volume (goal is to stow within 25% of operational volume) and rover mechanization approaches, high strength-to-mass structures and materials innovations (e.g. goal is 50% reduction in mass through use of composites), high power-to-mass actuation with reduced gearing volumes, improved thermal isolation and vehicular survivability, and reduced computation and power use in sensing and control. The sample return vehicle concept for FY "97 is a four wheeled rocker, with -20 cm diameter collapsible lightweight wheels, integrated structure/thermal chassis, on-board PC 104 computing, composite micro-arm sampling mechanization, and active/passive laser/stereo 3D sensing. Work on this task began in FY '96; progress to date include the LSR- 1 rover shown in Figure 4 which is 1 meter long, six-wheeled, 7 kg vehicle, carrying a multi-spectral imager [8,9].

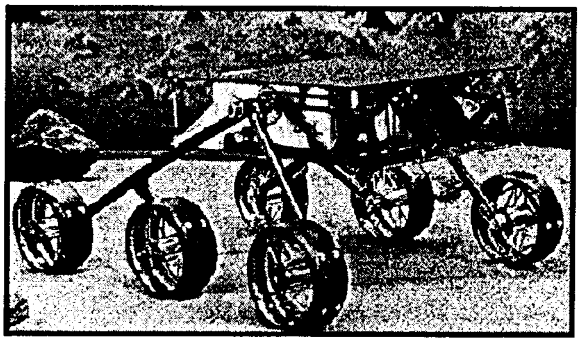

Figure 4- Lightweight Survivable Rover Prototype with Collapsible Wheels

2.2.1.3 Nanorover Technology

In our nanorover technology development effort, led by Brian Wilcox[10], our FY '97 goal is to demonstrate a nanorover with a mobility mechanism of the order of 100 grams performing a realistic mission scenario. This mission will include a traverse of at least 3 meters and capture of microscopic and infrared spectra. In FY '96 alternative nanorover concepts were created which were tethered to off-board breadboard electronics and evaluated (Figure 5). A nanorover system was selected which includes a four-wheel rocker-bogie chassis, self-righting mechanism, microscopic/ panoramic multi-band APS camera, and near IR spectrometer. A mechanism and printed wiring board were fabricated which resulted in a complete nanorover with mass of the order of a 100 grams.

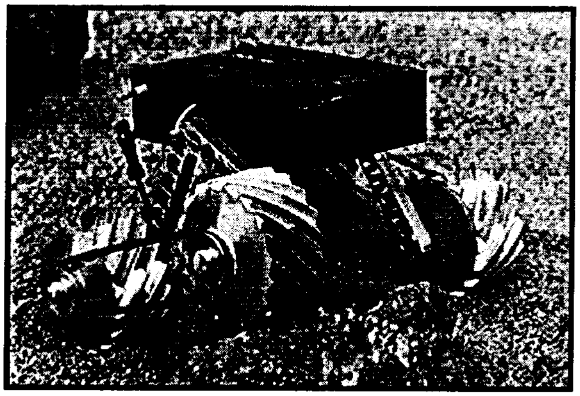

Figure 5- The JPL Nanorover

3.2.1.4 Planetary Dexterous Manipulators

The planetary dexterous manipulator task (Figure 6), led by Paul Schenker[8], develops robotic devices and component technologies enabling planetary surface science, with emphasis on manipulators, actuators and effecters for lander and rover based selection and processing of samples for Mars Surveyor Program missions, The scope of these operations include visually guided precision positioning and force controlled dexterous interactions of an arm/effecter with both soft granular and hard rock materials, all composite construction, fabricated in a 3D high strength machinable material.

3. SURFACE MOBILITY AND SAMPLING

Comets and small bodies, such as asteroids, are important targets for future exploration [11]. Both comet and asteroid missions involve landing on and anchoring in a low-gravity body and sampling its surface and

Figure 6- Novel Telescopically Deployed Arm for Mars Lander-Based Sampling and Analysis

subsurface — operations never before attempted. Landing in the extremely low gravity environment (ranging from 10-4 to 10-2 m/sec2) requires a method of retaining the lander to the surface, and rendezvous impact energy must be absorbed without causing the lander to merely bounce off. The near absence of gravity, and the assumed aggregated morphology of comets, hold the promise of the most rugged terrain ever to be landed upon. Science goals require that the lander cannot cause sublimation of the substrates to be sampled, resulting in design goals for operation at -120 degrees Kelvin. To meet these needs, a team led by Donald Sevilla[11], is developing technologies to enable in situ scientific studies of such interplanetary objects.

As an illustration, a prototype sampling system, which incorporates multiple sensors and allows autonomous operation as well as the gathering of data on material properties as sampling is done, is illustrated below. This system is designed to drill in cryogenic temperatures typical of cometary material (Figures 7).

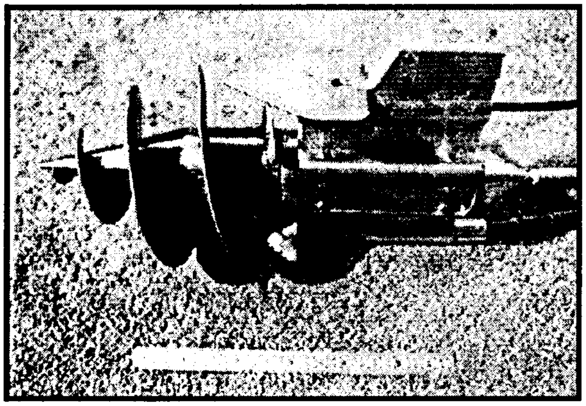

Figure 7- A Prototype Subsurface Explorer Developed in 1996

4. AEROVEHICLES

Planetary aerovehicles, or aerobots, are an innovative type of lightweight and low-cost telerobot, one that can fly and navigate in planetary atmospheric environments [12]. The challenges of flying a planetary aerobot are providing mobility and autonomous navigation in a constantly changing three-dimensional environment — one in which the robotic vehicle is almost never stationary. These challenges include real-time determination of the location and state of the aerobot, vertical motion control of the aerobot, and prediction and planning for global scale path trajectory. One type of aerobot involves a robotic balloon concept incorporating buoyancy control. This altitude control concept employs phase-change fluids such that a planet's atmosphere is used as a giant heat engine to provide the energy to ascend and descend at will — allowing the vehicle to visit multiple sites of scientific interest. This concept has been demonstrated in a free-flying terrestrial prototype. Aerobots offer the revolutionary capability to repeatedly visit the surface of Venus for several hours at a time and then rise high enough in the atmosphere to cool off (Figure 8). No previous technology such as passive balloons, probes, or landers can provide this capability.

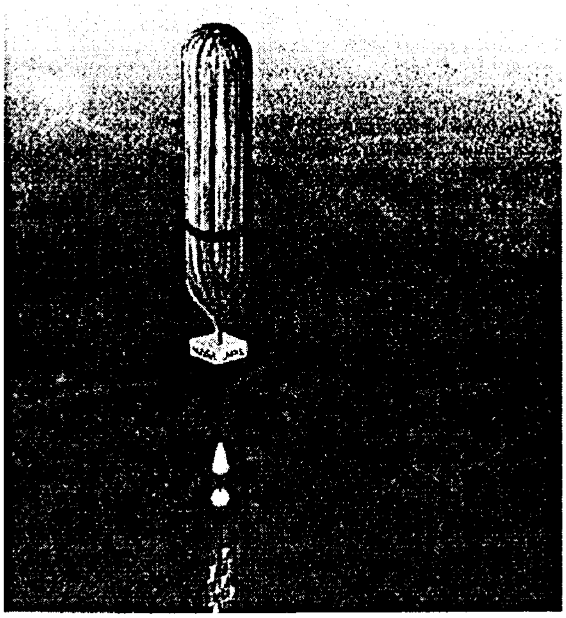

Figure 8- Artist's Rendering of an Aerobot, a Flying Robot, for Exploring Venus.

5. CLOSING REMARKS

By means of the technology development approaches outlined in the paper, the road is being paved toward providing enabling robotics technologies for in-situ exploration missions into the 21st Century.

ACKNOWLEDGEMENT

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