Evolving Directions in NASA's Planetary Rover Requirements and Technology

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1. ABSTRACT

This paper reviews the evolution of NASA's planning for planetary rovers (i.e. robotic vehicles which may be deployed on planetary bodies for exploration, science analysis, and construction) and some of the technology that has been developed to achieve the desired capabilities. The program is comprised of a variety of vehicle sizes and types in order to accommodate a range of potential user needs. This includes vehicles whose weight spans a few kilograms to several thousand kilograms; whose locomotion is implemented using wheels, tracks, and legs; and whose payloads vary from microinstruments to large scale assemblies for construction. We first describe robotic vehicles, and their associated control systems, developed by NASA in the late 1980's as part of a proposed Mars Rover Sample Return (MRSR) mission. Suggested goals at that time for such a MRSR mission included navigating for one to two years across hundreds of kilometers of Martian surface; traversing a diversity of rugged, unknown terrain; collecting and analyzing a variety of samples; and bringing back selected samples to the lander for return to Earth. Subsequently, we present the current plans (considerably more modest) which have evolved both from technological "lessons learned" in the previous period, and modified aspirations of NASA missions. This paper describes some of the demonstrated capabilities of the developed machines and the technologies which made these capabilities possible.

II. Large Mars Rovers for Sample Return: 1980's View

A. Robby

one of the approaches taken was embodied in a wheeled rover (designated Robby) developed at the Jet Propulsion laboratory under the technical leadership of B. Wilcox (1). Robby was built to allow development and demonstration of robust navigation and hazard avoidance techniques. It is equipped with all on-board mobility, power, sensing, and computation components to allow realistic long-distance traverses through rugged natural terrain. Robby is a six-wheeled, three-body, articulated vehicle that offers enhanced mobility compared to a conventional four-wheeled, single body vehicle. The three-cab design allows the front and rear cabs to steer and roll with respect to the vehicle center-line, and the vehicle hinges about the center axle as well to allow the six wheels to comply to complex terrain geometry. Robby is about 4 meters long, 2 meters Wide and 2.5 meters high and weighs approximately 2000 kg. A commercial robot arm mounted on the front body can be used, under force control, to acquire baseball-sized rock samples. The middle body contains an electronics rack to house the on board processors and other electronics, while serving as a mounting pedestal for the stereo camera navigation sensors. The rear body contains a commercial electric power generator, Four cameras are mounted atop Robby; various pairs have been used to produce stereo images. Stereo vision has been the sole source of rover-derived terrain data on Robby. For each planning cycle, three image pairs covering an approximately 80 degree field of view are captured and processed by stereo correlation. Figure 1 illustrates Robby navigating in outdoor terrain. in a test that took a little over 4 hours to complete, Robby performed a 100 meter Semi-Autonomous Navigation (SAN is described in Section C) traverse through rough natural terrain in the arroyo adjacent to the JPL facility.

More recently, faster speeds - 80 meters per hour and more, arc being achieved by using increased speed special purpose computer processors (a 68040 based CPU with 10 MIPS replaced a 68020 CPU) , improved algorithms, and mobility subsystem upgrades to permit speeds Up to 1 meter/ sec. in progress is a human controlled (i.e. CARD navigation [see see'. C] and teleoperated manipulation) experiment in which Robby navigates a triangular test course with 100 meter sides, picking up sample rocks at two corners and returning to he start location.

B. Ambler

A second large vehicle (designated Ambler and shown in Figure 2) was developed at Carnegie Mellon University, led by W. Whittaker, as a testbed for legged locomotion and planetary exploration (2),(3). A legged configuration was chosen both for reasons of mobility and energy efficiency. Typically, legged robots can cross more rugged terrain than wheeled vehicles due to higher ground clearance and the need to find only discrete ground contact points, rather than continuously traversable paths, Walking decreases energy requirements by reducing the number of energy-losing terrain/n~echanisn~ interactions needed to traverse a given region. 'l'he Ambler is configured with six legs, stacked on two central shafts. The shafts are connected to an arched body that supports four enclosures housing electronics and computing, including several processor boards and workstations. On-board power is provided by batteries and a propane generator. The Ambler has a number of sensors to monitor its progress and safety, including fail-safe load holding brakes, joint encoders, and limit switches. Six axis force/torque sensors mounted on each foot arc used to detect terrain contact, and two inclinometers on the body indicate

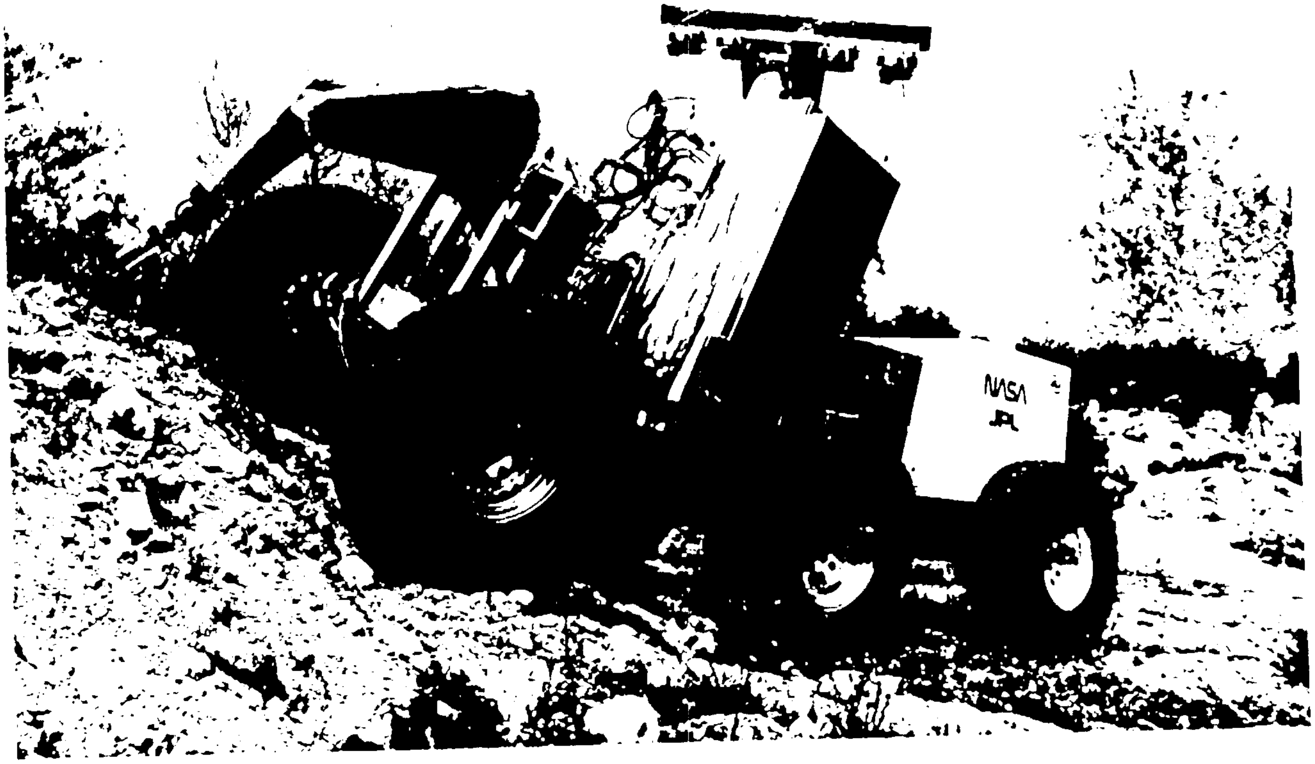

FIGURE 1 - **ROBBY**

A Wheeled Planetary Rover Test bed Navigating in Outdoor Terrain angular deviations from the horizontal plane. Perception of the terrain is provided by a forward-pointing scanning laser rangefinder.

The Ambler's legs are orthogonal mechanisms that decouple horizontal and vertical motions. The stacked legs and body cavity between the stacks make possible a novel "circulating gait", where the trailing leg on a stack recovers through the body cavity and past the other two legs on that stack to become the new leading leg. The circulating gait increases energy efficiency by decreasing the number of footfalls (and hence leg/terrain interactions) needed. The use of "level body motion" saves energy since the load on the horizontal links is reduced, enabling them to be lighter weight. Level body motion also simplifies control by reducing the number of joints that must be coordinated simultaneously and provides the Ambler's terrain sensors with a stable and predictable field of view. The Ambler's unique design provides for great mobility and energy efficiency. The Ambler was designed to cross one meter boulders and trenches while on a 30 degree slope. Its ground clearance ranges up to 2 meters, and its width can vary between 4.5 and 7.1 meters. For walking on sandy terrain, the Ambler needs about 150 W above steady state to move a single leg, and about 600 W above steady state to propel the body forward at 7.5 cm/sec. Steady state power consumption, mostly by amplifiers, fans, computers and other electronics is about 1400 W. The Ambler weighs approximately 3000 kg.

The Ambler has walked on sand, soil, and rocks, surmounted 1.5 meter high boulders, climbed up and down slopes, and walked at night (the laser scanner is not dependent on ambient light). in extensive trials, the Ambler has walked continually for many hours, covering several kilometers in total. Its average walking speed of about 40 cm/minute is primarily limited by the speed of the mechanism. In one particular experiment, the Ambler walked 107 meters and turned nearly 9 complete revolutions in negotiating several figure-eight patterns over boulder-strewn terrain. This involved nearly 400 body moves and over 900 meters of legged travel.

C. Alternative Control Strategies

Operation of rovers with some form of remote or semi-autonomous control is desirable to reduce the cost and increase the capability and safety of many types of missions. however, the long time delays and relatively low bandwidths associated with radio communications between planets preclude a total "telepresence" approach to controlling the vehicle. Different control implementations with varying degrees of human supervision can be contrasted; three of these developed at JPL are illustrated by Computer Aided Remote Driving (CARD) (4), Semiautonomous Navigation (SAN) (5,6), and Behavior Control (7). Each of these represents points on a continuous spectrum of human-machine interaction and other approaches, or hybrids of these could equally well be discussed. With CARD, stereo pictures from the rover are sent to Earth, where they are viewed by a human operator using a stereoscopic display. The operator designates a path using a 3-D cursor, giving a safe path for the vehicle to follow as far ahead as he can see accurately in three dimensions. A ground based computer computes the turn angles and path segmant distances that correspond to the designated path. The information is then uplinked to the rover for execution, and the process repeats. With Semiautonomous Navigation, local routes are planned autonomously using range information obtained on the vehicle, guided by global routes planned on Earth using a topographic map which is obtained from images produced by a satellite orbiting the planet of interest. Expectations are monitored, and a percept ion-planning-monitoring-execution cycle is instantiated. in Behavior Control, an approximate range and heading to a goal location is uplinked to the vehicle which attempts to reach its destination by autonomously instantiating sensor- based reactive behaviors of varying complexity. These might include obstacle avoidance, search for specific features, sample acquisition, etc. Behaviors can be combined and layered to give more robust and richer overall system performance. important considerations in choice between alternative control techniques concern robustness, predictability, and validation for mission use on one hand, and computational, sensor, and other resource requirements on the other.

To reliably and safely control the Ambler, CMU developed an autonomous software system which uses a conservative, deliberative approach somewhat analogous to SAN: each Ambler motion is carefully planned, checked several times for feasibility and stability, and executed while monitoring sensors on the robot for signs of trouble. The software system consists of a number of distributed modules (processes), each with a specific functionality: real-time control, perception, planning, task-level control, and error recovery. The modules are integrated using the Task Control Architecture (TCA), which provides utilities for distributed communication, subtask coordination, resource management, execution monitoring and exception handling(8). Modules communicate by passing messages via a central control module, which coordinates and synchronizes their actions. The perception subsystem uses data from the scanning laser rangefinder to build 3D elevation maps of the terrain (9). The planning subsystem consists of gait, footfall and leg trajectory planning modules. The gait planner combines kinematic and pragmatic constraints to find a sequence of leg and body moves that maximizes forward progress (10). The real-time control subsystem performs three basic functions: it provides reliable, accurate control of all eighteen actuators, it maintains the robot's dead-reckoned position and orientation (1 1), and it monitors sensors to maintain the Ambler's integrity. During leg motion, the controller monitors the force sensors to detect terrain collisions, halting motion within 5 msecs and raising an exception when unexpected collisions occur. The controller also monitors the inclinometers, automatically leveling the robot when the tilt exceeds a given threshold. As an extra safeguard, a hardware safety circuit is used which sets the brakes and shuts down all motions if anomalies (such as amplifier faults) are detected. This combination of deliberative and reactive approaches has been found to be quite effective in practice, enabling the Ambler to operate for extended periods of time. The software system has been used to autonomously navigate the Ambler over rugged terrain, both indoors and outdoors.

111. **Development** of Micro rovers and Associated Technology

Due to the problems involved with advocating and implementing a large, costly project with the dramatic potential for single point failure, NASA planners in the office of Space Science and Applications and the office of Exploration have changed their focus to the development and deployment of a number of small rovers to do science and exploration missions which can serve as precursors to later manned, or larger robotic missions. This includes a complete system (i.e. microrover, lander, and control station) developed from the outset using science requirements and potential flight constraints as drivers (plausible mass, power, communication, and computation). The next mission to Mars currently under study, after Mars Observer, is MESUR, standing for Mars Environmental SURvey, wherein four separate launches over a five year period (1 999-2003) will each deliver four landers to Mars, establishing a network of 16 small (roughly 1 meter in diameter) surface stations distributed globally from pole to pole. It is likely that the MESUR mission will consider significant use of microrovers. The science thrust embodied in the proposed MESUR mission is focussed toward Mars missions involving instrument deployment, sample acquisition, image analysis, etc. within 10-100 meters of the lander.

In conjunction with the shift in direction of NASA's planners to an interest in small rovers, NASA's research program has developed a number of such devices. These include the Rocky series and the Go-lior robot which are described below. The Rocky-4 robot was the first JPL microrover designed to explicitly show that microrovers combined with microinstruments provide a technology base of direct interest and usefulness to Space Exploration missions (such as MESUR).

A. Rocky-4

The design of the Rocky-4 mechanism was under the technical direction of D. Bickler. The Rocky-4 chassis is a springless suspension system called the "rocker-b ogic," which consists of two pairs of rocker arms or "bogies. " Each pair consists of a main rocker arm and a secondary arm whose pivot point is at the front end of the main arm. The two rocker-arm assemblies are connected through a differential gear at the center of gravity. The main body of the robot is mounted on the differential. The pitch of the main body is thus the average pitch of the two rocker-arm assemblies, providing a stable mount for instruments and sensors, Rocky-4 is 61 cm long, 38 cm wide and 36 cm high. The rover has six 13 cm diameter wheels made of strips of steel foil and cleats to provide traction. It weighs about 7 kilograms but eventually will have to be scaled down to 4 kg for inclusion in the final MESUR Network mission set. There is a motor in the hub of each wheel so the vehicle. can be steered by its front or rear wheels. The suspension system is unique in that it does not use springs and provides a great degree of stability for traversing rocky, uneven targets including rocks as high as 18 cm. Proximity and tilt sensors are used to prevent rollover.

Rocky IV carries two science instruments: a visible light spectrometer, with a range of 0.5 to 1.0 microns, and a color camera. Other equipment include a chipper to pare thin coverings of material from rocks, a soft sand scoop to take soil samples, and a seismometer tethered to the lander that Rocky-4 will be instructed to emplace at some designated surface location. Rocky 4 is illustrated in Figure 3.

B. Go-For

The Go-For vehicle (so named since it's primary mission would be to Go For samples, images, spectra etc.) was developed under the technical direction of B. Wilcox. Go-For is used to investigate microrover-based Computer-Aided Remote Driving (CARD), and the use of surface property sensing to ensure safe traversal over unknown terrains. Go-For is 40 centimeters long and 40 cm high in its normal cruise posture and weighs 3.5 kilograms. The innovation of the Go-For microrover is the ability to traverse very large obstacles and rough terrain due to a novel "fork-wheel" design. The vehicle has four wheels which are mounted on the "forks" (pairs of struts which can rotate together on the ends of an axle through the body). A control system adjusts the fork positions so as to keep 80% or more of the weight of the vehicle over the rear wheels in its normal stance. This gives the rear wheels the traction needed to thrust and lift the front wheels over obstacles as much as 70% of the stowed vehicle length. Furthermore, if the vehicle is overturned, the forks are powerful enough to right the vehicle. Appropriate. positioning of the forks would also allow gentle deployment of a seismometer, scooping of soil, or pointing of the camera to get closeups of interesting rocks, The overall system concept is to use the lander for all possible resources due to the relative ease of high-bandwidth communication between rover and lander. This means that the microrover can be essentially "teleoperated" by the lander computer, with continuous speed and steering commands emanating from the lander. Robby has been used as the simulated lander in the first series of experiments. Go-For is illustrated in Figure 4.

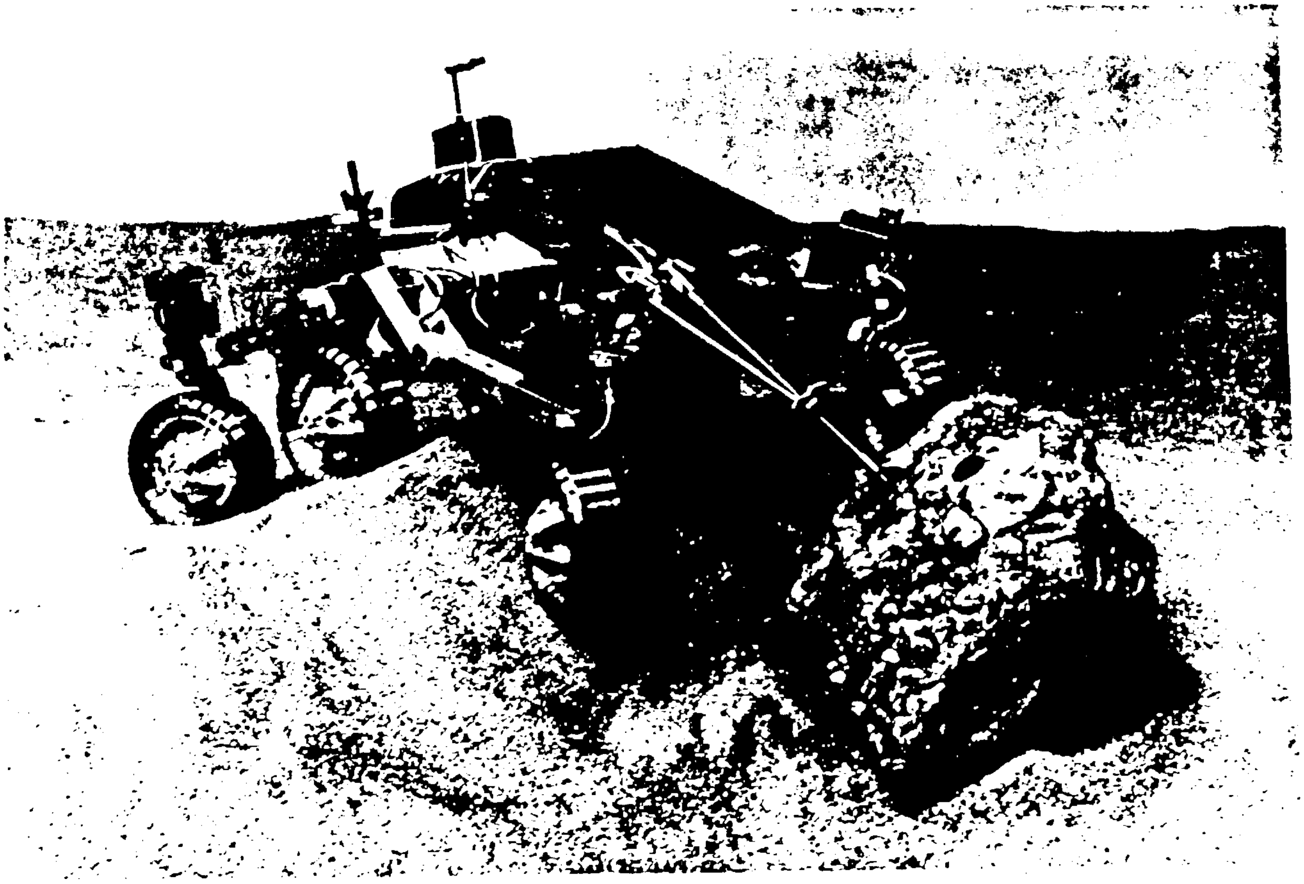

FIGURE 3 - ROCKY-4

The Rocky-4 Microrover Test bed Developed in Support of the Mars Environmental Survey Pathfinder Program

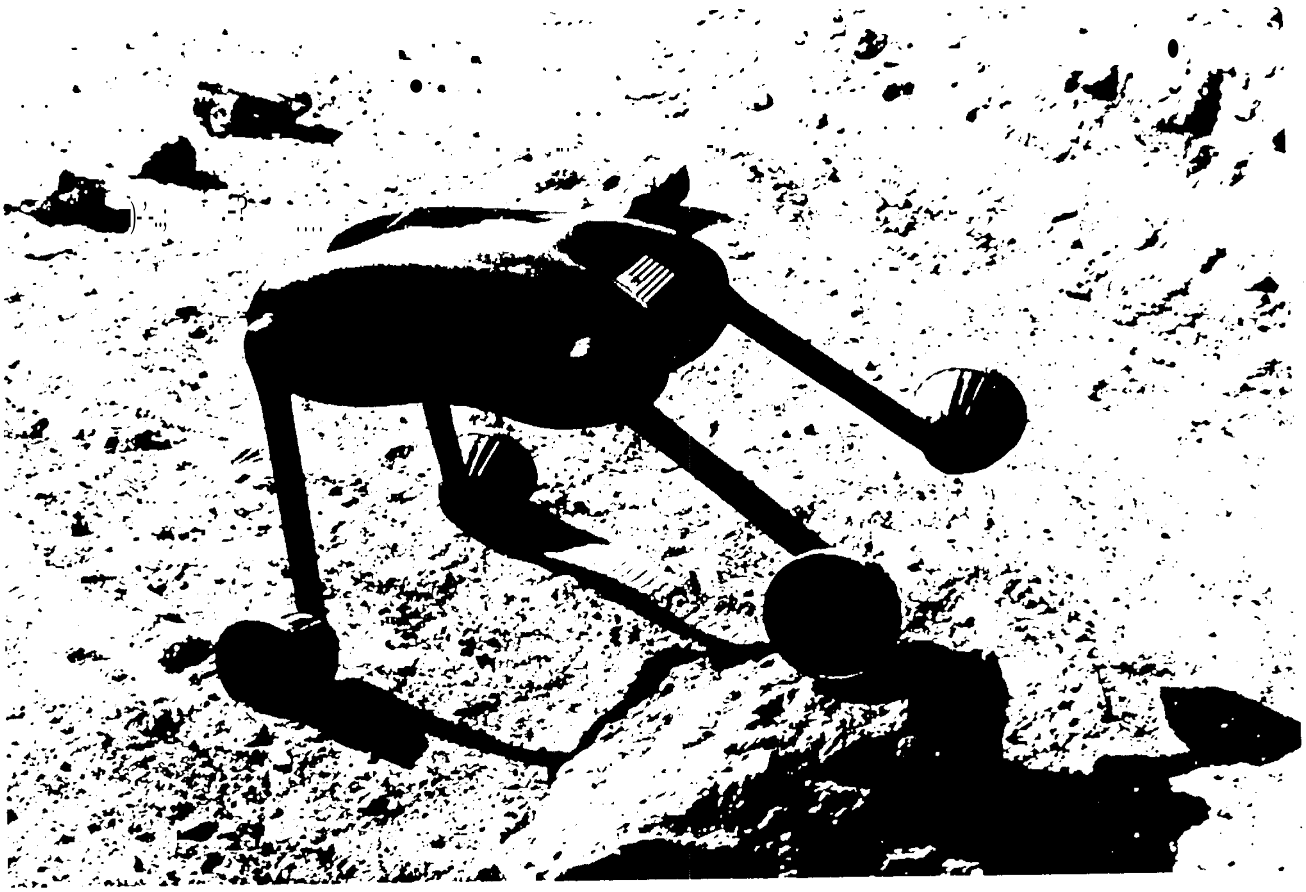

FIGURE 4 - GO-FOR

The Go-For Microrover **Testbed,** Used to Investigate Surface Property Sensing, Can Upright Itself Should It Fall

C. Mars Science Microrover Demonstration

A ground based demonstration of relevant capability, under the technical direction of A. Lant, was performed at JPL in June 1992 using Rocky-4, The experiment demonstrated the (a) ability to deploy a small(<150 gm) seismometer within 5-10 meters from the lander, (b) ability to acquire a soil sample and return it to the lander, (c) ability to integrate and operate a small (<500 gm) spectrometer to determine mineralogical composition, (d) ability to conduct visible imaging (camera < 150 gm) of local terrain, (e) ability to navigate in a field with rock distribution similar to that seen in Viking 1 and 2 missions, and (f) ability to remove 10-30 microns from a weathered rock to perform spectrometry.

Other important considerations emerging from this first experiment suggest further study. These include provision (if required) for safe operation of the rover without line-of-sight to the lander. This could involve the addition of proximity and ranging sensors on the microrover, fusion of ranging at the lander with imagery captured directly on the rover, addition of stereo on the rover for terminal corrections, etc. Another possibility is to localize the rover from the lander more precisely through map generation and maintenance. A number of technology and design measurements need to be made which quantify the paths taken by the rover under various sceneries, determine designation accuracies, test macro-commanding options, measure the traffic ability of terrain, etc. In addition somewhat more flexible (e.g. 2-D vs. 1 -D) manipulation capability should be tested for instrument emplacement capability, surface grinding, sample acquisition etc. improved algorithms for data compression can make a significant contribution. Finally, tradeoffs of tether management vs. autonomy and flight electronic/software constraints needs to be further evaluated.

Later missions are anticipated to involve multiple small rovers (2-4 kg each) with a much greater capability for autonomous operation at distances up to 10 km from the lander. These missions could be followed by Mars sample return missions employing 10-20 kg rovers operating from 1 to 10 km from the lander and returning rock samples to it.

IV. Development of Minirovers and Associated Technology

Two mobile robots developed under the leadership of W. Whittaker of Carnegie Mellon University (Erebus Project) are being developed to explore an active volcano, Mount Erebus, Antarctica by year-end 1992. The scientific objectives of the project are to determine the composition of gas generated by the lava lake, measure the temperature of the lava itself, and collect samples of sublimates and soils in fumaroles. The technical objectives of this program are to achieve extended autonomy, environmental survival, and self-sustainable mission performance in the harsh Antarctic climate, which demands as much of a robotic explorer as any location on Earth. This mission will set an important precedent in mobile autonomous operation and accomplish a necessary step in planetary exploration by achieving goals that arc part of the joint NASA/NSF program to use Antarctic analogs in support of future space exploration.

During the mission, the two robots, a transporter named Virgil and a rappeller, Dante, will work as a team, Virgil, is a skict-steered wheeled robot whose principal function is to carry Dante to the volcano crater rim, navigating the mountain with local terrain sensing. The robots will ascend the mountain by traveling 60km from McMurdo station, first over-ice then up slopes of Erebus to a habitable mountainside base station established about 2km from the crater rim. After completing the final 2km ascent to the summit, Virgil will anchor itself and Dante will begin its descent into the crater. Dante will negotiate the crater wall by sensing the local terrain, groping with its legs and using its tether as a climbing rope, Within the crater Dante will perform remote sensing operations and make photographic records. Upon reaching the crater floor it will acquire samples of gas and sublimates. It will then climb back up its tether to Virgil, mount up and return to the base camp. Human operators will interact with the exploration robots from the base station that will house controls, displays and computers to process user commands and robot data. In order to achieve success in the face of many unknowns, a flexible user interface with modes ranging from teleoperation to human supervision to full autonomy is necessary. A second command point will be established in the U.S. and linked to Erebus via satellite. Using NASA's Tracking and Data Relay Satellite System (TDRSS) video and data will be transmitted from Antarctica allowing researchers in the U.S. to observe and control the robots,

Virgil is an eight wheeled skid-steered mobile robot. Each wheel has an independent active suspension for high performance in cross-country locomotion. It is propelled by a modified aircraft engine which is rated for high altitude and can provide the power necessary to ascend steep slopes. Virgil is approximately 4m in length, 2.9m in width and 4000kg in mass. Steep ascents in the glaciated area of the upper slopes will likely be teleoperated. Dante is a eight legged walking robot. It is approximately 3m in length, 1.8m in width, and 400kg in mass with eight pantographic legs. Feet arc fitted with capaciflector sensors developed at the NASA Goddard Space Flight Center, a proximity sensor which uses a flexible capacitive film to detect distance to nearby obstacles, On Steep slopes a tensioned tether will provide the reactive force to gravity, assist in maintaining equilibrium, and allow Dante to rappel like a mountain climber.

V. Conclusions

The NASA program has addressed a variety of vehicle sizes and types in order to accomodate a range of potential user needs. This includes vehicles whose weight spans a few kilograms to several thousand kilograms; whose locomotion is implemented using wheels, tracks and legs; and whose payloads vary from microinstruments to large scale assemblies for construction. Earlier rovers were designed for the Mars Rover Sample Return requirements: high mobility, long range, long endurance, high autonomy, flexibility to perform many tasks. Robby and Ambler were two of the important navigation testbeds developed during this period to demonstrate the state of achievable technology. These large vehicles (2000 kg for Robby and 3000 kg for Ambler) demonstrated autonomous navigation over harsh terrain for hundreds of meters, but the vehicle mass and power requirements (even when significantly downs caled) were seen as prohibitive by current planetary mission designers.

Due to the problems involved with advocating and implementing a large, costly project with the dramatic potential for single point failure, NASA planners have changed their focus to the development and deployment of a number of small rovers to perform science and exploration missions. This includes a complete system (i.e. microrover, lander and control station) developed from the outset using science requirements and potential flight constraints as drivers, Two such microrovers developed for NASA are the Rocky-4 and Go-For vehicles which are described in the text. Ground based testing has shown the capability of microrovers to conduct visible imaging (camera <150 gm) of local terrain, navigate in a field with rock distribution similar to that seen in Viking 1 and 2, deploy a small seismometer(<1 50 gm) within 5-10 meters of the lander, remove 10-30 microns from a weathered rock to perform spectrometry, determine mineralogical composition of rocks using a small (<500 gm) spectrometer, acquire a soil sample and return to the lander. Current control systems for realistic scenerios have the human operator setting broad" goals (e.g. navigation way points) and monitoring system performance; system autonomy accounts for local obstacle avoidance and safety reflex behaviors.

With respect to new developments of larger scale robots, an exciting initiative underway is the development of a a team of two robots whose purpose it is to explore an active volcano, Mount Erebus, in Antarctica at the end of 1992. The technical objectives of this program are to achieve extended autonomy, environmental survival, and self-sustainable mission performance in the harsh Antarctic climate, which demands as much of a , botic explorer as any location on Earth. This mission will set an important precedent in mobile robotic operation, and accomplish a necessary step in planetary exploration by achieving goals that arc part of a joint NASA/NSF program to use Antarctic analogs in support of future space exploration.

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