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Local navigation and obstacle avoidance will utilize a model based feedforward control system. The system simulates the behavior of the vehicle on several candidate paths and excludes hazardous trajectories. The simulation uses a sensor generated terrain model and accounts for vehicle dynamics and position uncertainty in computing the hazard of a path. This classification of paths can autonomously generate commands to move toward a desired goal or can act as a safeguard and supervisory backup for human-commanded driving.

Navigation and position estimation combine star navigation, inertial navigation, natural and artificial landmarks. This information feeds path planning algorithms to generate optimal paths for accomplishing long traverses.

Virtual reality technology will allow both commercial and science customers to best utilize the imagery and data return. Methods of electronic pointing and stabilization will allow exploration of the lunar world with high fidelity. Topographic mapping of images along with science data will engender a new form of remote, geoscience exploration.

4.2. Plan

The lunar rover is combining navigation, stereo, global planning to be demonstrated in a multi-kilometer traverse by summer 94 on Ratler, a mobile chassis developed by Sandia National Laboratories. In 1995 we will develop a lunar relevant mechanism, power and communication system. This effort will culminate in a 100 km traverse, and later to 1000 km after further refinement and hardening. The earth based demonstrations will prove the technologies and rational configurations for the flight article design. The development of the lunar prototype will include extensive testing of components and systems simulating reduced gravity, vacuum, extreme temperatures, radiation, dust endurance and launch conditions.

4.3. Summary

Three mobile robots, developed in the context of space applications, are profiled here. One targets extreme terrain and volcano exploration, one is intended to service heat tiles during ground processing of the space shuttle, and one targets long range, long duration exploration of the moon. They share commonalities from software and computing to sensing and actuator technology. They differ in the specifics of purpose, mission environment, physical configuration and maturity. Dante will explore the Mount Spurr volcano in July 1994, Tesselator will begin acceptance tests at Kennedy Space Center in May 1994, and the Apex robot will demonstrate incremental capabilities toward a lunar traverse in 1998. In the broader context, they provide a sampling of roles and status of mobile robot utility for applications in space context.

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The primary objectives are to motivate mass participation by providing a realistic experience of lunar exploration, and to perform lunar science. High quality video from the rover will provide panoramic views around the rover. Amateurs will have opportunities to take the controls and drive. A fourth of the mission is intended to address science goals.

The Lunar Rover project will substantially advance planetary exploration technologies. The project will push the limits of mobile communication, teleoperation, robotic safeguarding and durability of a machine in the harsh environment of the lunar surface. Other issues include autonomy, telemetry, delay, and high-reliability software and hardware. The LunarTrack project will be a milestone towards the long range goal of extensive lunar exploration and commerce.

The Field Robotics Center (FRC) at Carnegie Mellon University has joined with LunaCorp and others to fulfill this project. We are enrolling agency and commercial investors to support the venture. Customers such as television networks, theme parks and program producers are buying time on the rover for commercial, scientific and exploration purposes. The enterprise has research funding from NASA, cooperative research with DOE, and initial commercial investment is in place.

Our strategy is to build a rover that embodies mechanical simplicity, robustness and capability. Robotic technologies of navigation, vision, real-time control and self-regulation will be incorporated to enhance and safeguard the rover. Camera imagery will provide data for robotic operation, science and virtual reality.

4.1. Rover and Technologies

We anticipate a 200 kg class rover that will fly on a Phobos class lander. The primary technical challenges are to:

- Return continuous, video (about 3 Mb/s compressed) while driving at slow walking speed.
- Survive unfiltered solar radiation, cold of -180C and operations in heat of 130C.
- Accomplish an unprecedented traverse of 1000 km and two years of operation in these extreme conditions on a surface of fine, electrostatic dust.

The moon offers opportunities for rich solar power and direct telemetry to earth, but presents substantial environmental challenges. The communications link, propulsion, computing and payload motivate a 300 W class power system. Video telemetry requires unprecedented precise pointing of a high gain antenna from the moving robot. Heat, dust and radiation motivate an enclosure to protect the power system, computing, transponder and other payload. The enclosure will be heated at night, possibly using phase change materials and resistive heating. Critical surfaces including solar array, radiators and lenses must be covered during landing, dawn and dusk.

Terrain sensing will principally use stereo mapping and proximity sensors. Stereo mapping involves extracting range information from matching areas in one image to others taken from different cameras with known positions. This method is fast and robust since it uses cameras whose behavior in harsh environments is well understood. An array of proximity sensors will additionally safeguard the body.

Software is a substantial component of the Tesselator system. Access to a research robot, Uranus [Blackwell 90] allowed us to begin testing planning and navigation algorithms well before the actual Tessellator hardware was ready. For instance, by specifying the interface between the planner and the base controller in a generic "virtual vehicle" fashion, the planner can be run without requiring any knowledge of what vehicle it is actually talking to. Since the TCA commands and queries serviced by both Tessellator's and Uranus's controllers were identical, switching between the two robots is simply a matter of attaching one or the other controllers to the planner's network.

For base motions we selected the following method for course of robot action: Notify operator, move only with deadman switch actuated by operator. Reasons for this selection include that the robot can drive more smoothly and directly than the operator. Additioanlly with the override control, the operator can stop the motion easily at any time and observe progress of the robot in the course of a move. This also allows a simple to implement upgrade path for the software for autonomy.

Our goal from the beginning has been to allow a full upgrade path to autonomy in both hardware and software and to provide a self-reliant system. In system design this has meant provisions for all on-board power and supplies that might have been supplied through a tether. At the same time issues of safety and many ‘what-if' scenarios had to be considered. The decision was finally for the operator-override option. This was no different than the full-autonomy mode but allowed the robot to be shut down at any time by the operator.

To protect both flight hardware and the robot, we are using proximity sensing around the base and sections of the manipulator. Contact bumper strips surround the base, but during base motions an operator is primarily accountable for robot actions. This was an interesting development as a result of trying to certify multiple safety sensors and accounting for failures of safety sensors.

At the beginning of a shift, the Tessellator is downloaded a job. The job consists of a series of files describing tile locations, sequences, target id's, orbiter parking measurements etc. The job is created on the Workcell Controller, an off-board workstation that is used to both create jobs and update other NASA databases after the robot uploads data gathered during the course of the shift. This data includes tile images, records of tiles injected or inspected, and other pertinent job data. In addition robot status data is used to monitor robot operation as well.

This section outlined the tasks,rationale, and facility requirements for the development of an automated tile servicing system. Salient features included omnidirectionality, high reach, high stiffness and accuracy with safety and self-reliance integral to all aspects of the design. The robot aspires to unprecedented specifications for a mobile-manipulation system.

4.0 Lunar robot with rich telemetry for realistic remote experience

We are embarking to send a robot to the moon in 1997 to perform a two year, thousand kilometer traverse, visiting the historic landing sites of Apollo 11, Ranger, Surveyor and Lunakhod. This rover will represent a return to the lunar surface after more than 20 years.

electronics in bulky explosion- proof boxes (which can contain any hot combustion products if the contents were to explode). We use a sealed thin-wall enclosure, and use the nitrogen to keep it purged of atmosphere and at a slight positive pressure. With this scheme, there is no way for explosive gasses to leak into the presence of the electronics. To keep the main electronics enclosure cool without an atmosphere exchange, two heat pipes are used remove heat. The tool plate also employs a thermoelectric cooler.

All of the electronic enclosures are purged and pressurized, including the battery pack. When the battery pack is off- board for charging, it is ventilated to prevent the accumulation of hydrogen gas (a by-product of the lead acid chemical reaction).

3.8 Computing

Tessellator carries four on-board computers (Figure 2) and accesses one off-board database. The hardware and software of the on-board systems is based on a design employed successfully by a number of CMU's other robots.

Three of the on-board computers are VMEbus based real-time systems: a robot controller which controls the base and manipulator motions and monitors the overall health and status of the robot; a vision system which performs the registration and inspection tasks; and a waterproofing system which controls the waterproofing injection system. The hardware for these systems was chosen to meet performance, power budget, size and packaging constraints.

The two computer systems which directly control actuator motion (robot controller and waterproofing system) employ "safety circuits" between the computer servo outputs and the motor amplifiers. This piece of hardware has a large number of analog and digital inputs which monitor various system values, and functions as a smart fuse. In the event any parameter goes out of bounds (for example: motor current, enclosure temperature, or low battery level), the safety circuit removes power from the amplifiers and brakes, effectively locking the actuators. The computer can then query the safety circuit for the cause of the shutdown and take corrective measures. Reacting to out of bounds conditions at a hardware level insures a fast response time and removes the burden from software.

The fourth on-board system is the high level planner. The planner is responsible for planning the course of action to complete a given task and appropriately commanding the subsystems. In the case of an error or failure in any system, primary safing is performed at a low hardware level via the safety circuits, and the planner performs recovery actions. The planner also maintains a graphical operator interface, which allows the operator to load and update task parameters and stay informed about the progress of the current task. Additionally, the planner interfaces to the bar code navigation scanner.

Communication between the systems is via CMU's Task Control Architecture (TCA) [Simmons 91], which provides communication between software modules, goal tree generation and execution, resource management, and rudimentary error recovery.

3.9. Software

base-manipulator configurations the robot was designed from the beginning to integrate the two sub-systems of locomotion and manipulation.

The drivetrain suspension is a simple rocker-arm design much like those on heavy construction machinery. This was very simple and top robot speeds are slow enough (30 cm/sec) that this is suitable for this application. The base supports two enclosures for electronics and rewaterproofing equipment as well as an on-board nitrogen tank and a battery cage.

When the base reaches a particular work area the stifflegs deploy and provide a rigid base to work from. The manipulator then begins to unfold itself from it's stowed configuration. The manipulator provides a number of motions, some redundant, to reach the tiles.

3.5 Positioning and Navigation

To achieve accuracies of 1mm across the underside of the orbiter we utilize two systems. A rotating eye-safe laser scanner reads bar code targets that are precisely located in the facility. Triangulation from three or more of the many targets can give us robot position with a few centimeters. This will position us precisely enough to find a specific tile. The tile positions are known very accurately with respect to the shuttle and we can register the tile position with the vision system we are using for inspection.

There are several frames of reference and corresponding transforms between them. The Orbiter is parked within some position error which is known and measured as a normal procedure. This gives us the orbiter-facility transform. Then the transform between the robot and facility is given by the laser positioning system and finally the loop is closed through the vision system which precisely identifies the position of a specific tile whose position is already known on the orbiter.This finally gives us a precise robot-orbiter transform.

Currently the positioning of the robot base during base motion is done simply through an interative positioning scheme. The dead-reckoning of the wheeled machine is quite good but we have augmented this with an on-the-fly Kalman technique to provide rapid position updates.

3.6 Electronics and Power

The electronic design of Tessellator is driven by two major constraints: It must run un-tethered for up to 10 hours (one 8- hour shift plus setup, employment, and deployment time). Fifteen kilowatt-hours of battery power would need to be carried on-board. A main bus voltage of 144 volts DC was chosen to meet motor torque requirements, and also lends itself to efficient DC-DC conversion. The battery pack is removable via a palette-jack, and the entire battery pack is charged off-board the robot. The robot can be powered through a tether for testing and in case of a battery failure.

To meet the safety requirements imposed by DMES it is necessary to meet National Electrical Code (NEC) class 1 division II requirements for operating in a hazardous atmosphere. To meet the explosion proof requirements, it is necessary that nothing that could potentially spark or reach flash point temperature be exposed to the atmosphere. This is usually accomplished by packaging

The number of tiles serviced at a setup determines the frequency of base moves.   A goal of approximately one base move per half-hour was set. Once per half hour translates roughly into 80 moves during the course of rewaterproofing the orbiter. This argues for a workspace of 300 tiles. A reduction to 250 tiles in the workspace gives 100 moves, or a base move every 24 minutes. With approximately 15,000 tile servicing steps it is important to note that a reduction of 1 second on the tile servicing time results in an approximate 4 hour reduction in total task time.

The tessellation and base move issues combine to provide insight into robot configuration and use. With a workspace of an appropriate size the overall time can be minimized while keeping robot size within the facility constraints. For 150-200 tiles, that workspace size is approximately 3.5-4.5 m2. Note that the area of the robot base is approximately 2.5m2 which means that an arm must reach out beyond the perimeter of the base. This was already recognized however, since some tiles are above obstacles that the base cannot intrude upon, such as the jackstands.

3.4 Robot Design

The design considered a wide variety of robot options that allowed inspection from afar, large fixed but movable, manipulators and even suction-cupped walkers. These ideas became detailed examinations of a wide variety of robotic devices. Many options were rejected on the grounds of flexibility, issues of self-sufficiency, safety to personnel or flight hardware etc. As a result of these preliminary studies the system we focused on was that of a mobile base integrated with a manipulator system.

The size constraints of the vehicle coupled with the close quarter navigation needs for operating in the OPF required a locomotion system of high maneuverability. A wheeled system utilizing Mecanum wheels was selected [Blackwell 90] which utilizes novel roller wheels to obtain three-degree-of-freedom (DOF) motion in the plane, pure rolling contact for accurate positioning, and non-singular motions for small and precise final motions. The system uses four controlled DOF's to obtain a 3DOF system. The fourth degree of over-constraint is controlled and detectable. [Muir 88]

The drivetrains for locomotion are within the diameter of the wheel hub and consist of a brushless DC motor, resolver for positioning and commutation, a brake for safety reasons, a cycloidial reducer providing 225:1 gear reduction with exceptional stiffness, and a locking hub that couples the output of the reducer to the wheel. The locking hub allows the operator to disengage the wheels from the drivetrain completely. In an emergency this provides a means to tow or push the machine out of the way.

The drive system is able to move the robot over 10cm high steps and up 20% grades. Although the rollers are not soft and have a high durometer rating they are compliant enough to affect accuracies of the system at full reach. The need to lock out this compliance and provide a stable non-compliant platform resulted in the use of automated screw jacks to descend from the base and contact the floor. Current threshold is used to determine contact and provide some indication of force.

The base is formed by very rigid welded steel frame. The design was not stress driven; rather it is deflection driven to provide a very stiff base from which to operate the manipulator. Unlike most chemical, DMES, which is injected into each and every tile. There are approximately 17,000 lower surface tiles covering an area that is roughly 25m x 40m.

DMES is injected into a small hole (about 0.1cm) in each tile. A nozzle is held against the tile and the chemical is forced through the tile by a pressurized nitrogen purge for several seconds. The tile heights range from 290cm to 400cm from the floor. It takes about 240 man-hours to rewaterproof the tiles on an Orbiter.

During launch, reentry and transport a number of defects can occur on the tiles. These are evident as scratches, cracks, gouges, discoloring, and erosion of surfaces. These defects are examined to determine if they warrant replacement, repair or no action. The typical procedure involves visual inspection of each tile to see if there is any damage and then to assess and categorize the defects according to detailed checklists. Later, work orders are issued for repair of individual tiles.

3.2 Design Constraints

Facilities and procedures at the Kennedy Space Center constrain robot design. The work areas can be very crowded. Perhaps the facility constraint with the most impact is the requirement to enter the work area through personnel access doors (1.1m wide). The layout within the facility allows a length of 2.5meter (100") for the robot. In addition, there are structural beams whose heights are as low as 1.75m (70"). Thus, the height, width and length of the robot are limited by facility dimensions. However, once under the orbiter the tile heights range from about 2.9 meters to 4 meters. Thus the robot must be compact to enter and maneuver in the vacility, then has to reach upward to the tile heights and work with 1mm accuracy. Additional constraints include the negotiation of jackstands, columns, workstands and overcoming cables and hoses and their protective covers. In addition there are hanging cords, clamps and hoses.

One of the tenets of the project is to impact the current tasks and flow as little as possible. This means performing the same tasks in at least the same amount of time and providing equal or better quality. People are understandably cautious about robot systems in close proximity to flight hardware such as the Orbiter. The paramount concern is safety to the personnel and the Orbiters.

DMES is flammable and toxic requiring all electronics to meet Class I Division II of the National Electrical Code (NEC) spnecs. Our solution is to use intrinsically safe (incapable of sparking) components where exposed and to purge electronic enclosures with gaseous nitrogen.

3.3 Design Issues

There is a direct relationship between the size of the robot workspace and the number of tiles covered. As one might expect, the larger the workspace, the greater the number of tiles covered for each robot move and setup. What is not so obvious are the effects of the workspace size on the time that it takes to visit all the tiles. For example, if the robot has a small workspace, then the time to stow, move and re-deploy may dominate the overall time, not the actual processing of the tiles. Analysis reported elsewhere evaluated the effects of workspace and mechanism movement time on the design. The important result from this work was that a workspace of more than 150 tiles per base move was necessary for overall efficiency.

tactical commands. Software like Dante's TCX is broadly applicable to space missions that incorporate autonomy in a distributed high-level software system.

Dante's analog technologies also include onboard terrain modeling for safeguard and navigation—essential for missions that wander long distances on the planets. Dante senses ground contact and uses this to monitor internal forces and external equilibrium. Planetary robots will use such full models of mechanical state for insuring tipover safety.

The Spurr technologies and communication via satellite telemetry will demonstrate the kind of rich display and control that is possible for robotic missions in lunar, shuttle and station contexts. The live video feed will demonstrate the subject and quality of imagery that will be possible for remotely experiencing lunar terrain.

The performance of the technologies at Mount Spurr will calibrate future, more ambitious objectives. We hope to excite the scientific community, so that we may learn the right reasons for and objectives of future exploration missions. We are attempting to make the mission to Mount Spurr as analogous to an actual planetary mission as possible but for practical reasons have not addressed, flight-qualification of components, extraterrestrial deployment or communication scenarios, or power generation issues

3. A Robot System for Ground Servicing Operations on the Space Shuttle

Maintenance of the shuttles is lengthy and costly. Turnaround time is typically three to four months. The process begins within minutes after landing and ends just prior to launch. Of the many activities in ground processing of spacecraft and payloads, inspecting and rewaterproofing the Thermal Protection System (TPS) of the Space Shuttle is a task of opportunity for a robot. It offers high payback, could be automated in relatively short time and forces the issue of robots engaging flight hardware.

Issues of safety, time savings, quality and reliability further motivate this initiative. The materials and chemicals associated with TPS tasks are dangerous to humans and require suiting up and cordoning off work areas during operations. It is possible for a single machine to do the work of several people, not only reducing hazardous exposure in some cases but also man-hours associated with that task. By providing accurate first-pass measurements and verification, rework is reduced. Many of the TPS tasks are highly repetitive and fatiguing overhead. A benefit that can save many hours and forms is the incorporation of automated data recording and information transfer. The resultant data integrity and complete and accurate reporting is of great value in tracking and planning work.

3.1 Rewaterproofing and Inspection

The Orbiter is covered with several types of heat resistant tiles that protect the orbiter‘s aluminum skin during the heat of reentry. The tiles are 95% air by volume which makes them extremely light but also makes them capable of absorbing a tremendous amount of water. Water in the tiles causes a substantial weight problem which can adversely affect launch and orbit capabilities for the shuttles. Since the orbiters may be exposed to rain during transport and on the launch pad the tiles must be waterproofed. This is accomplished through the use of a specialized hydrophobic gases. We will validate extremely remote operation of a robotic walking system and demonstrate Dante's ability to deploy scientific equipment and gather real-time data.

From a research perspective we will validate robotic technologies including a walking robot configuration, robot control architecture, robot control methods, communications, and terrain imaging and mapping. We intend to demonstrate autonomous control for some segments of the mission and to teleoperate others.

2.1 Dante Robot

Dante's eight pantographic legs are organized in two groups of four which alternately support and advance the robot [see Figure 1]. On steep slopes, the tensioned tether cable provides a reactive force to gravity, assists in maintaining equilibrium, and allows Dante to rappel like a mountain climber. Dante can rappel up and down steep slopes and surmount obstacles as large as 1 meter high. Dante receives its power and telemetry through the tether cable, making it an ideal deployment platform for multi-day remote scientific data gathering. An on-board gas-chromatograph is used to sample fumarole gases and relay composition information to remote scientists. A scanning laser rangefinder is used to perceive and model the terrain surrounding the walker. Planning software uses the terrain information to determine safe paths and adjusts the gait to avoid obstacles. For the Mt. Spurr mission, Dante will operate in a self-reliant wireless mode, with no people on the volcano rim, interacting via satellite with operators that are 130 kilometers distant from the volcano.

Our robotic exploration technique offers new field techniques for volcano research. Now a robotic machine, under the direction of scientists located in a safe remote location, can slowly and carefully examine and sample the inside of a volcanic crater without jeopardizing human safety.

2.2 Space Analogs

The mission analogs between Dante's exploration of Mount Spurr and future planetary exploration are from areas of locomotion, survival, and self-reliance. Dante is a unique walking mechanism that provides important insight into high-mobility locomotion. Beyond robot-specific technologies, our research addresses issues in design, fabrication, and operation of complex electromechanical systems. The missions we undertake intentionally challenge us to ruggedize the robots to survive in difficult environments. Mount Spurr will provide the access to and experience of difficult terrain that is not attainable with moderate terrain robots and minimalist sensing, processing and telemetry. We will learn about how to perform proposed planetary missions with the payback of accessing ambitious terrains with highly capable robots.

The terrain inside a volcanic crater forces us to develop tethered operating scenarios and advance the state-of-the-art in robot motion control. Dante's layered autonomy is a viable control model for planetary missions. By developing inherent reflexes and behaviors in Dante's ability to walk, we learn about how to make robots robust and productive. Our objective is enable Dante to continue to operate with only minimal will enable a wide variety of in-situ measurements and experiments not otherwise possible. Walking locomotion is uniquely advantageous for the challenge of crater exploration: a walker can avoid undesirable footholds, optimize stability, and move its body independent of terrain details (Bares, 1991). Using a variety of control modes, walkers have demonstrated very rough terrain capabilities undersea and on a variety of terrestrial sites (Ishino et al., 1983; Pugh et al., 1990; Simmons et al., 1991; Onodera, 1989).

A robot is an excellent platform from which to conduct scientific and data logging activities because of its innate abilities to measure position using internal sensors or external devices, such as satellite positioning systems. Temporal and environmental data can be added to the positional information to yield a complete record of sampling conditions. Mobile robots have been used successfully for similar tasks including mapping contaminants on hazardous waste sites, surveying construction sites (Kishishita et al., 1992), and measuring seabed topology (Onodera, 1989). Adapting these robotic technologies to the scientific study of active volcano craters had not been attempted before this project.

An ideal control mode for a volcanic explorer is a “supervisory” mode in which a human overseer monitors the robot’s progress and is relieved of the navigation tasks and can therefore focus on performing scientific observations. The robot is given high-level directives such as “move ahead 10 m” after which it must sense the terrain, plan its actions, and execute the actions in a safe manner. Experience with other mobile robots at Carnegie Mellon has shown that supervisory control is possible even in rough terrain situations (Simmons et al., 1991; Kelly, 1993). Key to the success of supervisory control is the timeliness, quality, and density of terrain data from which the robot automatically generates its motion plans (Hebert and Krotkov, 1992; Hoffman and Krotkov, 1993; Kweon and Kanade, 1990).

The Dante robot will demonstrate realistic exploration missions, rough terrain locomotion, environmental survival, and self-sustained operation in harsh, rugged, environments. Active volcanos in the Earth’s polar regions are targeted as terrain and climatic analogs to cratered and mountainous planetary environments. An additional outcome of demonstrating volcano exploration is that priority science data, historically unobtainable, can be procured in a safe and consistent manner. Dante carries a variety of scientific instrumentation used to determine the chemical composition of fumarole gasses. Following Dante's attempt to explore Mount Erebus, Antarctica in January 1993 (Wettergreen et al., 1993a; 1993b), NASA is supporting reconfiguration, development and testing for an early summer 1994 mission to Mount Spurr, Alaska.

Objectives for the Mount Spurr initiative are in the areas of locomotion of extreme terrain, withstanding environmental challenges, remote operation of a walker, and performing volcanic science from a robot. We intend to demonstrate that Dante is capable of traversing escarpments and exploring craters in environmentally challenging environments. Dante must competently ascend and descend steep and rough terrain requiring tether assisted walking. The robot must also be able to withstand the environmental challenges of cold, high winds, high humidity, and exposure to acidic

THREE MOBILE ROBOTS FOR SPACE CONTEXT

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1. Introduction

Space applications like planetary missions, ground servicing and launch operations differ from those for orbit and deep space. The presence of gravity distinguishes these missions from orbiters and fly-by probes. Advantages of gravity include the opportunity to use it for stabilizing and driving locomotion and to exploit commonalities with earth technologies and experience. Disadvantages include structural, actuation and power issues that are more significant in a gravity field. Case robots within this class differ substantially in capabilities, scale, purpose and environmental concerns, depending on context. This paper profiles three mobile robots, with research and operational objectives, in current development. The Dante robot is an octopod walker configured for scientific exploration of extreme terrain like volcanoes on earth and craters on the planets. The Tessellator is an omnidirectional robotic worksystem for ground operations such as servicing and rewaterproofing tiles on the space shuttle. The Apex robot is a lunar rover which will convey a realistic experience of the moon, perform science and motivate mass participation in exploration, including opportunities for live viewing and amateur control. Dante will explore the Mount Spurr volcano in July 1994, Tesselator will begin acceptance tests at Kennedy Space Center in May 1994, and the Apex robot will demonstrate incremental capabilities toward a lunar traverse in 1998.

2. Robotic exploration of craters and extreme terrain

Planetary surfaces are primarily cratered terrain. Some regions, like the lunar mare, offer mild locomotion challenges, but substantial regions present extreme difficulty for surface robots. Much mountainous terrain on earth is inaccessible to surface vehicles. Although atmosphere and weathering make craters less prevalent on earth, volcanoes are features of scientific interest that currently defy robotic exploration. Manned entry into active volcano craters is dangerous and typically yields sparse and incomplete data. Volcanic eruptions, both major and minor, pose a constant threat to explorers and caused the deaths of eight volcanologists in 1993 (Kerr, 1993). Further impediments to manned expeditions into volcanic craters include steep and treacherous terrain and changeable weather conditions. When missions are attempted, scientific equipment is restricted due to weight and bulk, and duration on the crater floor is usually held to a minimum to assure safety. Experiments lasting several days, though desirable, are infeasable, and the use of real-time analysis equipment is unrealistic due to weight, size, and energy requirements. The appeal of a remotely-controlled robot is that in the event of an eruption or failure, only the robot is in jeopardy.

Robotic helicopters (Normile, 1993) may provide basic video imagery, though scientific uses are unclear. Limited payload capacity and energy supply, as well as the difficulty of stable remote control will limit the usefulness of this approach as a means to conduct extensive scientific data gathering and analysis.

A mobile robot that can move within a volcanic crater in a stable and predictable manner