5 Conclusions

The Dante project developed and demonstrated rappelling locomotion in natural terrain. During its seven day mission Dante traversed what we believe is the most severe terrain yet attempted by a mobile robot. A contextual control architecture that greatly facilitated shared control between human operators and automated behaviors was conceived and demonstrated. The project also demonstrated remote volcanology by providing video and gas sensor data to scientists in several locations who could view, interact, and interpret exploratory results instantly and safely.

The nature of exploration is that the unexpected will be encountered and everything cannot be predicted in advance. This ambiguity must be anticipated in a robot's design, testing and operational safeguards. The terrain inside Mt. Spurr's crater was much more severe than expected from early reconnaissance, and conditions worsened during the mission. We believe that the success of the Dante project is in part due to the lessons described in this paper.

Is the Dante system appropriate to serve as a terrestrial volcanologist? Perhaps not in its present form. However, we believe that some of the lessons learned can be used to form the basis for next generation terrestrial explorers and future generations of their planetary counterparts.

Acknowledgments

This work was supported by the NASA Space Telerobotics Program under Grant #NAGW-1175. Many of the lessons described here were hard to learn. We gratefully acknowledge the support and dedication of the Dante project team.

References

[Angle, 1990] Angle, C., Brooks, R., "Small Planetary Rovers", *Proceedings of International Conference on Intelligent Robots and Systems*; Tsuchiura, Japan, July, 1990.

[Apostolopoulos, 1995] Apostolopoulos, D., Bares, J., "Configuration of a Robust Rappelling Robot." *Proceedings of International Conference on Intelligent Robots and Systems*; Pittsburgh, PA, August, 1995.

[Bares, 1993] Bares, J., Whittaker, W., "Configuration of Autonomous Walkers for Extreme Terrain." *International Journal of Robotics Research*, vol. 12, no. 6. December, 1993.

[Boehmke, 1995] Boehmke, S., Bares, J., "Electronic and Telemetry Systems of Dante II." *41st International Instrumentation Symposium of the Instrumentation Society of America*, Boulder, CO, May 1995.

[Fong, 1995] Fong, T., Pangels, H., Wettergreen, D., Nygren, E., Hine, B., Hontalas, P., and Fedor, C. "Operator Interfaces and Network-Based Participation for Dante II" *SAE 25th International Conference on Environmental Systems*, San Diego, CA, July 1995.

[Ishino, 1983] Ishino, Y., Naruse, T., Sawano, T., Honma, N., "Walking Robot for Underwater Construction." *Proceedings of 1983 International Conference on Advanced Robotics*, pp. 107-114. 1983.

[Kishishita, 1992] Kishishita, T., Jo, K., Sako, S., Koga, S., "Unmanned Surveying System using Automatic Moving Vehicle". *Proceedings of 9th International Symposium on Automation and Robotics in Construction (ISARC '92)*, Tokyo, pp. 843-848. 1992.

[Krishna, 1997] Krishna, M., Bares, J. Mutschler, E., "Tethering System Design for Dante II," *Proceedings of the International Conference on Robotics and Automation (ICRA '97)*, Albuquerque, NM.

[Onodera, 1989] Onodera, S., "Several Examples of Robot and Automation on the Underwater Construction Work." *16th Meeting of U.S./Japan Marine Facilities Panel*, Seattle, WA. 1989.

[Oy, 1995] PlusTech Oy Corp., Technical brochure., Tampere, Finland. 1995.

[Pai, 1995] Pai, D. "Platonic Walking Beasts", *Proceedings of International Conference on Intelligent Robots and Systems*; Pittsburgh, PA, August, 1995.

[Pugh, 1990] Pugh, D., Riggle, E., Vohnout, V., Bihari, T., Walliser, T., Patterson, M., Waldron, K., "Technical Description of the Adaptive Suspension Vehicle." *International Journal of Robotics Research*, vol. 9, no. 2. 1990.

[Sheridan, 1992] Sheridan, T., "Telerobotics, Automation and Human Supervisory Control", *MIT Press*, Cambridge, MA 1992.

[Stentz, 1995] Stentz, A. and Hebert, M., "A Complete Navigation System for Goal Acquisition in Unknown Environments", *Autonomous Robots*, vol 2, no. 2, 1995.

[Thomas, 1995] Thomas, H., Hine, B., and Garvey, J., "Kilauea: A Terrestrial Analogue for Studying the Use of Rovers in Planetary Science", *Proceeding of the 1995 Conference of the Space Studies Institute*, Princeton, NJ., May, 1995.

[Waldron, 1987] Waldron, K., Kumar, V., and Burkat, A., "An Actively Coordinated Mobility System for a Planetary Rover". *Proceedings of the 3rd International Conference on Advanced Robotics*; Versailles, France. 1987.

[Wettergreen, 1997] Wettergreen, D., Bualat, M., Christian, D., et. al. "Operating Nomad for the Atacama Desert Trek", *Proceedings of 1997 International Conference on Field and Service Robotics (FSR '97)*, Canberra, 1997.

[Wettergreen, 1995] Wettergreen, W., Pangels, H., and Bares, J., 1995. "Gait Execution for the Dante II Walking Robot." *Proceedings of International Conference on Intelligent Robots and Systems*; Pittsburgh, PA, August, 1995.

offered no visual cues that would help an operator reconcile object size and distance from the robot. (A stereo camera system was also incorporated on Dante's mast but lack of calibration and training led to limited utility.)

Virtual environment interfaces can be used to improve an operator's situational awareness and to efficiently visualize complex terrain and vehicle state information. We found that high frame rate, level of interactivity, and ease of use were all contributing factors for achieving immersiveness and sense of presence. However, insufficient visual reference aids and accuracy of correlation between graphical models and physical objects can degrade operator performance and confidence.

While climbing out of the volcano, the scanning laser became dysfunctional after airborne volcanic ash coated its spinning mirror surface. Teleoperation became extremely tedious as operators were left to infer terrain geometry based only on video and leg position information. Progress slowed and safety margins declined until the tip-over occurred.

4.10 Self-sufficient mobile robots are suited for remote science

A ground-based mobile robot is an excellent platform from which to conduct scientific and data logging activities in part due to its innate ability to precisely position and measure position using internal and external sensors. Temporal and environmental data can be added to the positional information for a complete sampling history.Using ranging sensors, a mobile robot can quickly map surface topology to a resolution and accuracy that would require a human team many days to complete. A robotic vehicle can dwell for days, weeks or even months while collecting, analyzing and streaming data to scientists at remote control stations. In the event of dangerous event such as a rockfall, only the robot is jeopardized. Mobile robots have been used successfully for tasks including surveying construction sites [Kishishita, 1992] and measuring seabed topology [Onodera, 1989].

Once a mobile robot is placed in the field to stream data back to human overseers, highly interactive robotic science missions involving many scientists are possible using live video and data links. As demonstrated by Dante and more recently by the Nomad robot [Wettergreen, 1997], the nature of exploration has evolved to the point where scientists in several locations can simultaneously be in "mission control" and view progress, analyze data, and advise.

However, key to this new era of exploratory robots is a system design and method of deployment that eliminates human danger and minimizes costs. While deploying Dante at Mt. Spurr, significant human effort and expense was required to emplace the anchor and configure power, communications and logistical equipment at the rim of the volcano. Including the large robot, nearly three tons of equipment were transported to the volcano. Self-deploying systems (e.g., air drop "packages") are more practical on Earth and essential for space missions.

4.11 Overdesign can enable rapid development

A key challenge of the Dante project was to design and ruggedize the robot and support equipment to enable repeated testing, transport and deployment at a variety of sites culminating with the harsh volcanic environment.

A key factor in our approach was to overdesign components and subsystems to enable rapid integration and unexpected conditions during deployment and exploration. It has been our experience that robot system integration commonly stresses components more than actual operating conditions. One approach is to slow integration in an attempt to avoid control "mistakes" that could damage the electromechanical system. We believe, however, that it is much more expedient to add overdesign in components where possible and thus permit integration to proceed rapidly and with less concern for equipment damage. For instance, motors were sized to withstand long durations of stall current even though this condition was designed to be protected by software. Of course, overdesign is no excuse to skip proper control code design, simulation and off-line testing.

Overdesigned hardware also helps the robot survive the rigors of deployment (It may be that deployment and transport activities–rather than exploring in the volcano crater–were the harshest operating conditions that Dante had to face). By nature, an exploration mission will encounter unexpected conditions. We believe that a systemic development approach that stresses overdesign will also result in a system more suited for an exploration mission. A common result of overdesign however, is increased weight. Our approach was to prioritize reliability and durability, though we did make systemic efforts to minimize weight to remain relevant to space missions.

4.12 Operational failure modes are significant

Overall, reliability and failure modes were stressed in the design and preparation phases of the project because the working assumption was that if the robot failed while in the volcanic crater, human entry and repair would be forbidden. Component related failure modes and subsequent implications nearly became an obsession during the development process. Interestingly enough however, throughout the program we did not seem to spend sufficient time contemplating operational related failures and possible implications. Indeed even as the actual mission wore on, we became increasingly fixated on the likelihood of component failures and their effect. Operational failures such as teleoperating the robot into a tip-over condition or tether entanglement were not considered to the same extent. In retrospect, additional focus on possible operational failures would have been prudent.

4.13 Harsh field experiments drive program

One of the major accomplishments of the Dante project was that it was structured not only to develop new technology and approaches to remote robotic exploration, but that it was to demonstrate the technology in real, unforgiving environments. While the field deployment generated much publicity and interest, the key technical reason to take on such a committing experiment is that it focussed the entire team onto a clear quantifiable goal and forced technology that was capable of performance under rugged conditions. As a result, we believe that the Dante project has contributed to robotic science as one of the first unattended field expeditions.

tinuous human oversight is required to monitor progress and reinstate teleoperation when automated performance worsens or the robot's safety becomes a concern.

Continuous human oversight and safety response is impractical for terrestrial robots and impossible for planetary systems for which large communication latencies exist. An important research focus must be to embed robots with sufficient intelligence to know when they should cease autonomous operation and request human input. (The *gait* and *path* contexts–though not completed–were intended to reduce Dante's reliance upon human overseers.) Most "autonomous" mobile systems developed to date relegate this key decision to humans. Field robots will become more useful and practical when they are able to conduct safe operations without continuous oversight and *request* human assistance when needed. As robots take on increasingly challenging autonomous tasks this requirement escalates in importance.

4.8 Graphical presentation of telemetry improves operator performance

A teleoperated robot, instrumented with many sensors, each sampled at a high rate, can produce an overwhelming amount of information for an operator to comprehend. Much of this information can be distilled to a dozen or so critical values. But in addition to watching video imagery, which is itself a substantial volume of information, monitoring robot telemetry is difficult to sustain reliably and is ultimately fatiguing. A number of studies confirm this observation. [Sheridan, 1992] We developed a multi-page graphical user interface for this purpose. [Fong, 1995]

We have had a number of unsatisfying experiences with text-based operator interfaces—they invariably provide a daunting array of numerical information and an indecipherable collection of command codes. The graphical interface provided a refreshing change that was quickly adopted. We have found that a graphical presentation of robot telemetry simplifies monitoring of the critical information and improves operator performance both in their ability to comprehend the robot's state and their ability to teleoperate and interact with the robot over long durations.

Our primary objective in creating a graphical operator interface was to make it as easy as possible to operate Dante. We were motivated both to minimize operator workload and to make it possible for novices to quickly learn to control the robot. The following guidelines emerged:

- *Consistent appearance and interaction:* Similar or identical design throughout the interface allows operators to focus on robot actions rather than the mechanics of using the interface.
- *Functional organization:* It is appropriate to embed the functional layout within the interface to avoid operator confusion. The use of operational control contexts provides a unifying and simplifying perspective on human-machine interaction. This approach enabled us to concisely organize the interface so that commands appropriate for a particular type of function are grouped together.
- *Uncluttered layout:* Clean graphical design with qualitative or simple quantitative representations of sensor and state information allows quick assessment of current conditions. Numeric data provides precision and should support graphical features unobtrusively.
- *Simple command generation:* Clear, easy-to-use controls allow efficient, rapid command sequences. Easily modified values and reusable commands are important for reducing operator workload during teleoperation.
- *Visual indication of safeguards:* Different command safeguards are appropriate depending upon the situation and the types of commands being applied. Indicators that clearly reflect active safeguards reduce operator misconceptions and error.

Anecdotal evidence suggests that operators were able to run Dante longer, faster, and safer with the graphical interface. We also found that visitors watching operations were able to quickly grasp how the interface worked.

4.9 Terrain visualization is essential to exploration

A frequently updated model and visualization of the robot and surrounding terrain is essential if efficient and thorough exploration is to take place. Visualization of the robot and terrain together aides situational awareness. A full 3-D "virtual environment" interface was developed for Dante to provide operators an easy means to visualize the robot's stance, forces, and surrounding terrain topology. [Fong, 1995] The

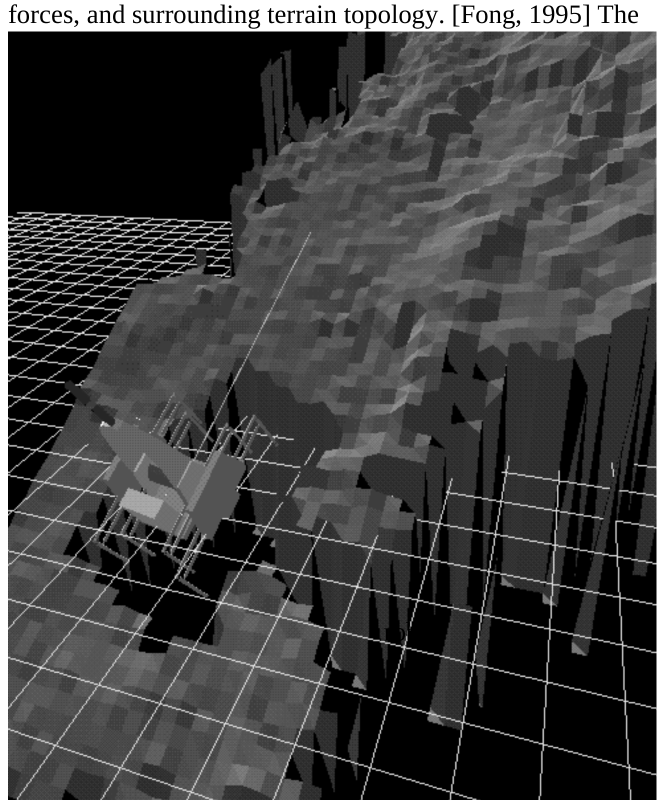

Figure 3: Dante virtual environment vehicle interface (grid denotes horizontal reference plane)

high resolution terrain data was provided by the scanning laser rangefinder. Using this 3-D interface operators could rather easily plan safe moves after studying the virtual robot and terrain from various viewpoints. In comparison, teleoperation from 2-D video imagery was very difficult because of a lack of depth information. Furthermore, the 2-D images ing execution, is insufficient for guiding a walking robot in natural terrain. Too much is unpredictable—events, like bumping obstacles or slipping off a precarious footholds, occur and cannot be foreseen while planning.

Reactive architectures address this problem by quickly relating sensation directly to action. These sense-act mappings establish planned reactions to expected, but unpredictable, events. Biological systems also provide evidence for simple sense-act reflexes and decentralized control in walking. At their neurological basis, these systems are constructed of inhibitory and excitatory links between neurons to create reflexes and with central pattern generators to sequence fixed patterns of action.

Both reactive and biological approaches possess properties necessary to gait execution: reaction to unexpected events, concurrency of reflexes, and coordination of actions. For Dante, we took an approach that benefits from these properties, and developed a network of behaviors to stand, posture, step, and walk. [Wettergreen, 1995] These behaviors use leg force and contact information as well as body attitude data to advance the framewalker across variable terrain. They establish a nominal gait to achieve forward progress and can individually react quickly to unexpected conditions. For instance, if the force on a supporting leg rapidly decreases due to terrain failure, a behavior will immediately initiate leg extension to regain support. The ability to adjust behaviors and guide their collective performance established Dante's supervised autonomy control mode. During testing and later during the mission, the behavior-based control operated the robot at its maximum speed and significantly faster than the most skilled human teleoperators.

4.6 Operational control contexts structure the degree of autonomy

A robot performs actions as the result of the coordinated control of its actuators. In one situation it may be necessary to control a single motion in a direct manner, while at other times may be appropriate to broadly guide only the coordinated result of many individual motions. A robot may be autonomous in some respects, but it is usually the case that at some point it takes external guidance. We found that it was effective to construct a software control system based on the idea that for an exploration robot, where the unforeseeable is commonplace, it may be necessary for a human operator to intervene at any level to control the actions of the robot. We designed control software in layers so that control signals could be generated by other software modules or by a human operator. We then developed the operator interface with specific control contexts which described which functions are performed by the robot and which are performed by the human operator [Fong, 1995].

To control Dante, the operator needs to apply different types of commands for different situations. We identified a collection of *operational control contexts*, which explicitly defined the set of commands and the information provided to the operator. In the case of Dante, these contexts are *Individual Actuator*, *Frame*, *Behavior*, *Gait*, and *Path*. Each context other than *Individual Actuator* adds elements of autonomy, as shown in Table 1. We found that these operational control contexts allowed us to unify and simplify the human-machine interaction and to establish a range of functionality from direct teleoperation to full autonomy.

Table 1: Operational contexts and degree of autonomy

Control Function	Actuator Context	Frame Context	Behavior Context	Gait Context	Path Context
Servo tether					
Coord. leg motion					
Maintain body hgt					
Maintain posture					
Adjust leg step					
Cross obstacles					
Perceive terrain					
Determine step hgt					
Determine body hgt		Operator Control		Automatic	
Determine posture					
Determine stride					
Adjust footfall					
Generate path					
Determine heading					
Avoid obstacles					

As an architecture, an organization into control contexts aids development by partitioning the system and clarifying interrelations. For instance, force-based leg control could be refined and tested even before the robot's body was completed. Efforts proceeded in parallel to build each control context. Though ultimately targeting autonomy, our development strategy was to build a solid teleoperation capability after which more autonomous capabilities could be layered on as developed. Then, if schedules slipped or technical problems arose with implementation of autonomous modes, the mission could proceed using only teleoperation.

As an approach to robot control, the contextual architecture simplified the challenging task of teleoperating a walking robot. The ability to access low-level functionality was crucial to extracting Dante from several exceptional conditions and tight spots. High-level functionality built upon robust low-level capability enabled more efficient operation in benign terrain.

4.7 Constant oversight limits autonomy benefits

An ideal control mode for a remote explorer is a "supervisory" mode in which a human overseer occasionally monitors the robot's progress and can therefore focus on scientific observation and mission strategy. The robot is given high-level directives such as "move ahead 10m" from which it must sense the terrain, plan its actions, and execute the actions in a safe manner.

Dante completed 25% of its descent into Mt. Spurr under the supervised behavioral control context. Since the behavior context only uses proprioceptive data, it is "blind" and cannot reason about complex terrain situations. As a result, con-

Our experience with Ambler however, showed that terrain adaptability may offer more flexibility than needed and stability is closely tied to planning and control [Bares, 1993].

Framewalking places fixed "constellations" of feet which offers a basic level of stability without relying on planning and control. However, if the foothold for any single foot is poor (e.g., on the edge of a boulder), the entire frame must be repositioned until satisfactory footholds are found for all feet on the frame. Once, crossing a 10m long testsite boulder field required more than four hours while Dante operators labored to avoid placing feet on the edge of boulders. A major improvement to the foothold selection problem would be to automate the search using a terrain elevation map.

In addition to inherent stability, framewalkers offer several key advantages for rappelling: First, since a rappeller is basically constrained to move down the fall-line, a mechanism specialized for straight-line motion such as a framewalker is ideal. Second, only two motions need to be synchronized to unwind the rappelling cable; winch rotation and frame translation. Even when crossing large obstacles and slope transitions, Dante rappelled smoothly with this simple control scheme. Alternately, a rappelling terrain adaptive walker would have to coordinate all supporting legs and winch payout to achieve smooth motion.

4.2 Rappelling extends capability but limits scope

A tensioned support cable can enable exploration of terrain otherwise impossible for a terrestrial vehicle to safely traverse. However, the obvious shortcomings of rappelling locomotion are the need for a reliable anchor and exploration range limited to the cable length. Dante's rappelling line is 300m; ultimately a line several times longer may be feasible for mobile robots, but size and weight of the rappelling system are real concerns. However, if all conductors could be eliminated from the tether through the use of on-board power and wireless communication, a dramatic decrease in diameter and thus increase in cable length could be realized.

While a tensioned cable can greatly improve the stability and terrainability of a robot along the fall-line of the slope, travel away from the fall-line creates restoring forces on the robot that try to move it back towards the fall-line. Restoring forces can cause the robot to slip sideways or even tip-over (a side pull from the tether aggravated the conditions that led to Dante's tip-over.) On very steep slopes, if the restoring forces overcome the frictional forces on the feet, the robot will swing much like a pendulum–a very dangerous condition for a mobile robot, especially if external sensors and appendages might be damaged. Maximizing a robot's obstacle crossing capability can reduce the need for travel away from the fall-line path. For this reason, Dante was designed with the ability to traverse 1.3m obstacles.

Anchoring will need to be automated by future rappelling robots as human deployment support becomes more difficult or impossible as is the case for planetary missions. Automated anchoring methods would have to vary widely depending on terrain materials and conditions. If an exploring robot could establish an anchor to assist in climbing–for instance by shooting a grappling line far up a slope–a new class of locomotion challenges could be addressed.

4.3 Self righting is unrealistic in most scenarios

After Dante tipped onto its side, a frequent question was whether some means of self-righting had been considered. There are several areas of key technical concern with self-righting scenarios: First, during a tip-over and possible subsequent tumble, it is likely that some devices such as terrain sensors, communication equipment, and actuators will bear the brunt of energy absorption and be damaged or rendered inoperable. Even if not damaged, communication and solar array equipment may only function when aligned upright.

The second fundamental challenge to self-righting is that most exploration robot tip-overs will occur due to static instability conditions, rather than dynamic instability. As a result, the robot cannot simply be "stood up" or righted again at the same location as it will immediately repeat the fall. Rather, some intelligence is needed to attempt self-righting that will not result in a repeated fall. A tip-over and tumble into a steep ravine could require a complex series of recovery steps to self-right to a safe stable stance.

Finally, even if the major issues of preventing damage and avoiding repeated tip-over can be overcome, we are faced with the final question of developing devices to enable self-righting. Such devices need to be high strength and should be capable of self-righting the robot from a variety of tip-over conditions. Rocket thrusters, airbags, helium balloons, and highly geared linkages have been suggested. Since such a device would only be used rarely it would need to be small and low mass as it represents lost payload capacity.

Several years ago Waldron proposed a multi-body wheeled robot that could self-right through a series of body twists. [Waldron, 1987] Recently, several exciting new walking robot configurations address the issue with mechanisms that can either walk upside down [Angle, 1990], or have no definition of "upright". [Pai, 1995] Even so, given the concerns for component damage during a tip-over or tumble and the need to avoid a repeated tip-over, it may be most appropriate to focus future research efforts on hardware and software approaches to anticipate and prevent tip-over.

4.4 A single electronics enclosure lowers risk

All Dante electronics were placed in a single sealed and shock isolated enclosure. The oversized enclosure was provided with heating and cooling for all expected development and mission conditions. From a reliability viewpoint, wiring connections are minimized and many are located within the protected enclosure. Since the enclosure environment was temperature maintained and shock protected, conventional "office grade" telemetry and computing equipment could be used for which hardened versions were cost-prohibitive or non-existent. As a result, we could quickly and economically explore experimental designs and options with computing, telemetry and video. During development, the single box could easily be removed for troubleshooting and repair.

4.5 Reflexes and coordinated behaviors produce tactical autonomy

We have been convinced, by our experiences with previous walking robots, that planning alone, without adaptation dur-

3 Expedition to Mt. Spurr

Mt. Spurr erupted three times in 1992 spreading 200 million cubic meters of ash over Alaska. Dante needed to rappel down the approximately 200m crater slope to sample fumarole vent gasses at the crater floor. The 20-45° slope was covered with snow, wet ash, mud, and meter size boulders and was complicated by a series of ridges and chutes.

Dante and support equipment were transported by barge, truck, airplane, and finally helicopter from Anchorage to Mt. Spurr. A short set-up period was required to install and arrange the various components on the volcano including a diesel generator and a satellite communication dish. Problems with a high-speed data link between the robot and rim telemetry station, and a damaged load cell on one of the robot's legs delayed the start of the mission for several days. Finally, Dante began its descent to explore truly unknown terrain—humans hadn't entered Spurr's crater since before the last eruption. Dante would continue to operate for the next five days with no humans on or near to the volcano.

The mission consisted of three segments; descent to the crater floor, floor exploration, and ascent to the rim. The upper section of the crater was covered with hard-pack snow across which Dante descended at about 1 cm/s in an autonomous rappelling mode using leg force sensors, pitch and roll sensors, and a behavior-based control scheme. As the receding snowpack boundary was crossed, the terrain became much more rugged and forced frequent use of an enhanced teleoperation mode that placed all critical control decisions upon the human operators. Meter-scale boulders were negotiated on a frequent basis as were ridges, chutes and complex slope conditions. Footing conditions worsened as Dante progressed lower into the crater and left the hard snowpack for deep mud and steep areas of ash. The snowshoes mounted to each leg were invaluable in limiting sinkage in the soft mud.

As Dante advanced farther into the crater, progress slowed not only due to the challenging terrain conditions but also because sensors could not see far enough ahead to avoid dead-end allies and intraversible areas. At least half of the time was spent retreating up the slope to try a new path around excessively large boulders or ridges. Another complication was an ongoing concern that the tether would become lodged between boulders far up the mountain: Dante's lateral moves were therefore limited to minimize the chance that the tether would become trapped and thus preclude future ascent. Though overall terrain slope lessened in the crater floor region, boulder size and density increased—with some boulders larger than Dante—making continued travel treacherous.

The laser-built 3-D elevation maps proved crucial to efficiently guide the robot and minimize retreats. In a common mode of operation, humans would set the direction of travel and then turn over control to the automated behaviors that would then enact efficient safe walking in the intended direction. When forced to revert to teleoperation, progress slowed by at least one order of magnitude as the human operators dealt with a huge amount of sensory data including video and laser data as well as vehicle state information. Though we had developed and begun to test software that enabled completely automated walking directly from the terrain maps, it was incomplete at the time of the mission.

Throughout most of the mission, and especially during the crater floor exploration, imagery was transmitted beyond Anchorage to the NASA Ames Research Center where geologists studied the crater and could control Dante's cameras. After two days of exploring the crater floor and detecting no liquid water and no sulfur compounds in the fumarole gasses, Dante began its ascent. Early in the ascent, all power and communication was lost to the robot. The culprit was found to be a moisture-related short circuit in the power cabling at the rim which was quickly remedied and the mission continued. Up to this point, the robot had operated five days without any human presence on the volcano and successfully achieved all of the mission objectives.

As Dante progressed out of the crater, the most difficult terrain was encountered. This was due in part to the fact that much snow had melted since the descent revealing harsh underlying slopes and boulders. Also, by the fifth day, the laser scanner mirror had become obscured by airborne volcanic ash and thus 2-D video images became the only means to view the terrain. Selection of safe paths became more difficult and much time was spent retreating back into the crater in order to try alternative exit routes. Ultimately, Dante fell on its side while under teleoperated control. The accident was due to a combination of factors including steep slope and cross-slope conditions, soft unstable slope material, a destabilizing tether exit angle, and a control algorithm that had never been tested in such perilous stability conditions.

In an initial attempt to salvage the robot by using a helicopter to lift it by the tether cable failed when the tether broke near the robot and caused the robot to tumble several times down the steep bouldered slope. Ultimately humans hiked to the robot, now less than 100m from the rim, attached a sling and successfully lifted it by helicopter. All other equipment was retrieved and the mission completed.

4 Lessons

The key lessons learned in the development and deployment of Dante are described in the following subsections.

4.1 Framewalking is suitable for rappelling

Walking mechanisms are excellent as the underlying locomotion means for a rappelling robot: Legs can enable the robot to cross very large terrain features without deviating from the fall-line and jeopardizing lateral stability. In very rough terrain a walking robot can avoid undesirable footholds, optimize stability, and move its body independent of terrain details. [Bares, 1993] Using a variety of control modes, walkers have demonstrated rough terrain capabilities undersea and on a variety of terrestrial sites. [Ishino, 1983] [Onodera, 1989] [Pugh, 1990] [Oy, 1995] At issue in the configuration of a walker is whether the mechanism should be a mechanically simple "framewalker" which advances groups of legs together or a more complex "terrain adaptive" walker that moves legs individually and is closer to animal analogs. Terrain adaptive walkers require more cognition and control to move legs but offer more flexibility in leg placement and gait.

2 Dante System Overview

The technical descriptions of the Dante system that follow are intended to provide a brief overview—consult the references on the Dante system for additional detail.

2.1 Robot Mechanism and Sensors

Dante is a framewalker; its eight pantographic legs are arranged in two groups of four, on inner and outer frames. [Apostolopoulos, 1995] Each leg can individually adjust its position vertically to avoid obstacles and adapt to rough terrain. Body translation is actuated by a single drive-train that moves the frames with respect to each other, depicted in Figure 2. To walk, the legs on one frame raise up, while legs on the other frame support. The free legs recover (in a group) to new locations as the frame translates, propelling against the supporting legs. The frames can also turn 7.5° relative to one another to change heading. Dante is statically-stable—it has no dynamic (balancing) phase in its gait cycle. But dynamic events certainly occur; bumps and slips can destabilize it. To rappel steep slopes, a tensioned tether, mounted on the inner frame, provides stability and minimizes adverse structural leg loading. When the inner frame is in motion, the tether is controlled to counteract the downslope component of gravity, and to minimize shearing forces at the feet. [Krishna, 1997] Dante has eleven primary actuated degrees-of-freedom (eight legs, frame stroke, frame turn, and tether) that are coordinated to move itself and regulate its posture (roll, pitch, and height).

Dante senses the terrain topography with both perceptive imaging devices, and proprioceptive position and force sensors. From atop the arch, a conically-scanning, laser rangefinder can measure the distance to the terrain in a 360° field-of-view. This depth map is transformed into an elevation map of the surrounding area, and used to identify obstacles or feasible paths. A pan-tilt camera set (including a variable zoom camera and a fixed focus stereo camera pair) is located under the arch and four other cameras are mounted low on the body to observe the legs and feet. Each leg has a load cell to measure vertical foot force, and a pair of strain gauges to measure loads in the translation direction. The strain gauges detect continuous high loads or transient bumps of small magnitude. Potentiometers encode joint positions and the tether angle and inclinometers measure gravity-relative posture. An assembly of constrained flexures and load cells measures tether force. [Krishna, 1997] Volcanic gas sensors are located under the electronics box, and a thermocouple is mounted to one of the leading legs for probing fumarole temperatures.

2.2 Computing, Electronics and Telemetry

The on-board computing hardware consists of three 68030 processors, one Sparc2 processor (for perception processing), two motion control boards, a DAADIO board, and several custom circuit boards, all mounted in a VME backplane. [Boehmke, 1995] Real-time control is distributed among the three 68030 processors, which run the multi-tasking VxWorks operating system. The first processor collects sensor information, with filtering from the DAADIO, and writes state into shared memory at 120 Hz. The second processor

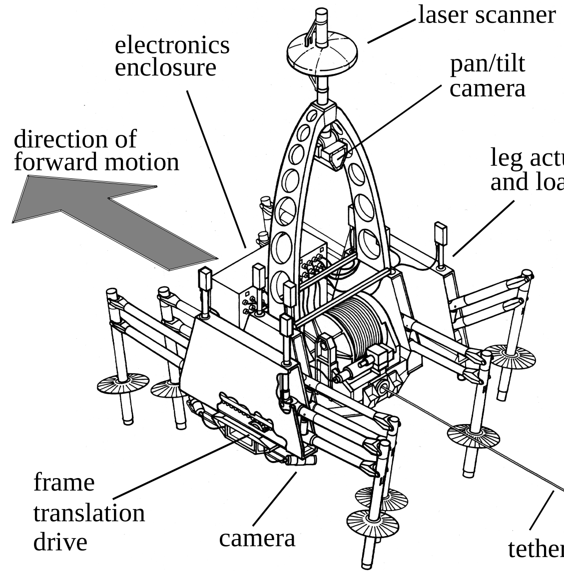

Figure 2: Dante Mechanism and Sensors

drives the leg servo-loops and services the motion control boards for the translation, turn, and tether actuators. The servo-loops generate trapezoidal velocity profiles from leg encoder values at 150 Hz to produce smooth motion. The third 68030 board runs the gait control processes which can access sensor values and servo-loops.

The on-board computers communicate off-board via a tether and satellite uplink. The tether is composed of a video coaxial cable and several twisted pairs, surrounded by load-bearing fibers. [Krishna, 1997] It provides power, communication, and physical support. The satellite uplink is 192kb with a round-trip delay of about 4 seconds. This is sufficient for monitoring robot state, although transmission of large data packets and network anomalies can cause delays of 30 seconds or more. As with most remotely-controlled systems, the telemetry bandwidth limitation and latency encourages on-board self-reliance and minimal external communication.

Power generating and conditioning equipment, video and data telemetry equipment as well as a site viewing camera are all located off-board the robot at the tether anchor point. A satellite band communications antenna also at the anchor site sends video and data between the robot and remote base station. [Boehmke, 1995] Operators in the remote station use graphical user interfaces to monitor and command the robot.

The robot is operated with five different contexts ranging from direct actuator control, to enhanced teleoperation, to autonomous control. [Fong, 1995] [Wettergreen 1995] Each context defines a certain mode of human-robot interaction and enables corresponding variables to be altered by the operator. For instance, in the behavioral mode of operation, the robot uses data from force sensors on the legs and inclinometers in the body to generate a motion sequence that safely adapts to the terrain. The human operator can instantly switch between contexts, for instance, returning to teleoperated control when a problem is detected during autonomous behavioral operation.

Lessons from the Development and Deployment of Dante II

John E. Bares
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213 USA
bares@cs.cmu.edu

David S. Wettergreen
Intelligent Mechanisms Group
NASA Ames Research Center
Moffett Field, CA 94035 USA
dsw@artemis.arc.nasa.gov

Abstract

Dante II is a unique walking robot that provides important insight into high-mobility robotic locomotion and remote robotic exploration. In 1994 it was deployed and successfully tested in a remote Alaskan volcano. For more than five days the robot explored alone in the volcano crater using a combination of supervised autonomous control and teleoperated control. The robot and field experiment are first overviewed to provide context for the focus of the paper—lessons learned. It is the degree by which we can learn from the Dante project that will determine its lasting significance.

1 Introduction

Guided by supervisory teleoperation and on-board autonomous control, Dante II rappelled into the crater of Mt. Spurr, an active Alaskan volcano, and operated alone for nearly a week exploring previously uncharted terrain and sampling volcanic gases. It travelled one quarter of its 165m descent autonomously, relying only upon onboard sensors and computers to plan and execute motions. Teleoperation by remote operators was used in situations beyond the capability of the autonomous system. Throughout the mission Dante streamed a variety of scientific data to operators and volcanologists located at two remote sites, the nearest being 120 kilometers from the volcano. While climbing out of the crater, the robot lost stability on a section of especially challenging terrain and fell on its side, ending the mission.

Several terrestrial robots have operated with more autonomy than Dante, but in much less demanding terrains and usually with close human oversight. As an example, the NavLab, with safety observer onboard, autonomously travelled several kilometers of moderate terrain in search of an obstacle-free path to a goal. [Stentz, 1995] Other robots have achieved long field missions, but required daily or more frequent human support. [Thomas, 1995] [Wettergreen, 1997]

The principal objective of the Dante project was to develop and demonstrate technologies which could lead to solutions for robotic exploration of rugged terrain on the Moon and planets. Robot autonomy is essential—due to the latency and bandwidth of communication to Earth, planetary explorers must be self-capable and succeed with only occasional human guidance. Human assistance for repair or rescue from entrapment is virtually impossible. Mt. Spurr–in addition to offering good lunar and planetary terrain analogs–forced a semi-autonomous system architecture because human operators were located far from the volcano for safety reasons, and communication bandwidth to the robot was limited due to site conditions. Mt. Spurr also offered a volcanically active crater that was unexplored by humans and therefore of some scientific interest. A secondary objective was to procure scientific data from the volcano to increase understanding of its level of activity and broaden experience in the use of robots as surrogate field scientists.

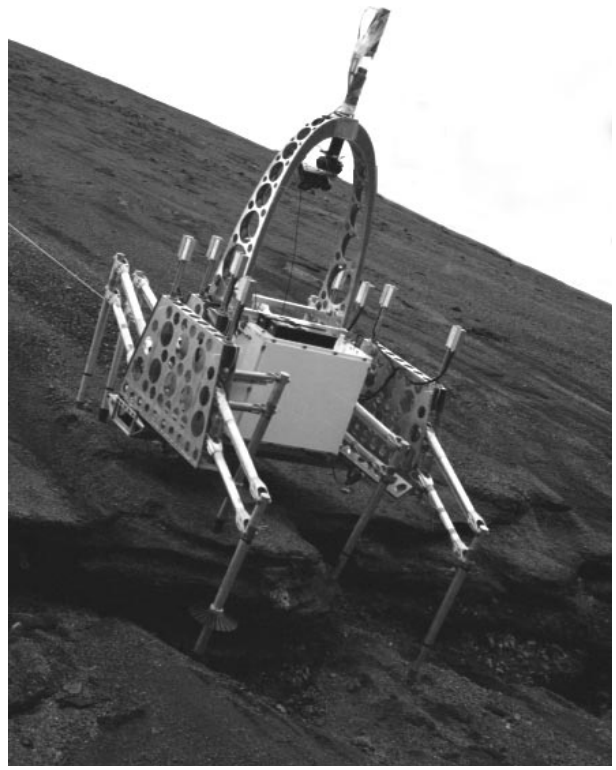

Figure 1: Dante crossing 1.3m step on 45° talus slope

The purpose of this paper is to discuss some of the key technical lessons that have resulted from the Dante project.