Locomotion Configuration of a Robust Rappelling Robot

Dimitrios Apostolopoulos John Bares

The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3891 USA

Abstract

Robotic rappelling is an intriguing concept for exploration of planetary craters and their Earth analogs, volcanoes. Integrating a tensioned tether to a framewalking robot enables a new statically-stable locomotive capability appropriate for rappelling on steep and rugged terrains. Rappelling with a tether-assisted framewalker also allows efficient execution of multi-level control. These ideas are manifested in the locomotion configuration of Dante II. The appropriateness of the Dante II configuration for rappelling was evaluated during a variety of tests and its 1994 exploration of the active volcano of Mount Spurr in Alaska.

1 Introduction

Robotic exploration of planetary surfaces involves traversing diverse and unknown terrain under remote and sometimes, infrequent human control. One of the most challenging situations is that of locomoting on steep terrain, which is typical of rilles, craters and highlands. This problem demands a suitable locomotion scheme as well as a means of control that enables human input at various levels of abstraction. To address some the engineering and operational issues related to remotely exploring steep planetary terrain, robotic missions to analogous terrains on Earth are highly useful. The barren terrain of terrestrial volcanoes possesses many common features with that of planetary craters. Furthermore, due to various dangers, robotic exploration of some volcanoes is only possible with humans located at very distant sites. Additionally, low bandwidth communication limitations between the robot and the human control station due to terrain topography, and challenging environmental conditions further make volcanoes appropriate sites for developing and testing robotic systems intended for steep planetary terrain.

The most critical requirement of robotic exploration of volcanoes is the ability to rappel on inclined terrain. Here, rappelling is defined to be the ability to locomote with the aid of a support member (tether) to maintain stability and apportion loads. The rappelling tether is anchored at the top of the inclined path and is unwound from an on-board winch. Rappelling on extreme terrain calls for robust locomotion configuration. Robustness is measured by the robot's ability to dominate performance requirements and to sustain rappelling progress even when challenged by unanticipated contingencies, such as slope failures or terrain collapse.

The physical limitations of on-board terrain-mapping sensors and the large amounts of data required to achieve complete perception of geometrically complex terrain, are limiting factors to the operational capability of an autonomous robotic rappeller. With the current state-of-art, autonomous supervisory control can be used to navigate a robot through mild terrain. However, as terrain difficulty increases low level teleoperation becomes appropriate. A multi-mode control architecture is therefore needed to enable both human teleoperation control and supervised autonomy for navigation through varying terrain conditions. The locomotion configuration is the cornerstone to the successful implementation of both teleoperation and autonomous control strategies and should therefore be rationalized to accommodate so-called multi-mode shared control.

The Dante II configuration is a straightforward solution to the problem of rappelling in rugged terrain. The configuration couples an optimized framewalking topology with a force controlled tension winch to provide a solution to robust rappelling. Dante II demonstrated its rappelling capabilities in extensive field trials on steep slopes covered with soft soil and slag, and during the exploration of the volcano of Mount Spurr in Alaska where it rappelled on ash and deep snow, performed numerous slope transitions and surmounted meter size boulders. Dante II achieved unprecedented capabilities for walking robots in harsh and remote environments.

0-8186-7108-4/95 $4.00 © 1995 IEEE

2 Robotic rappelling

Extreme sloped terrain, as can be found in volcanoes is characterized by steep inclines, slope transitions, large obstacles, ditches, overhangs and gulleys (Figure 1). So-called "combined features" such as a boulder on a slope or a ditch crossing a slope are common. The slopes and cross-slopes, frequency of combined features, soil properties, scale and geometry of natural obstacles determine the locomotive difficulty of negotiating the terrain.

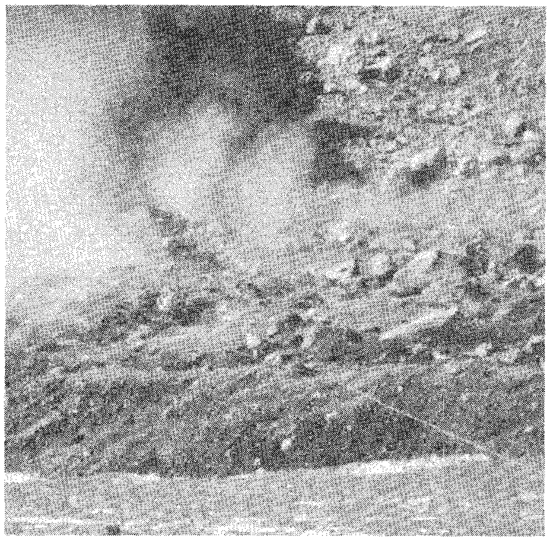

Figure 1: Dante II in the Mount Spurr crater. Cross-slopes (lower center) and boulder fields dominate the landscape

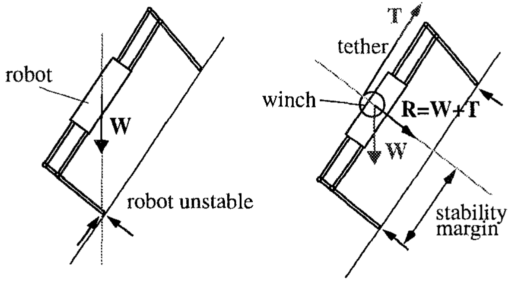

Figure 2: The tether stabilizes the rappeller and reduces leg loading parallel to the slope

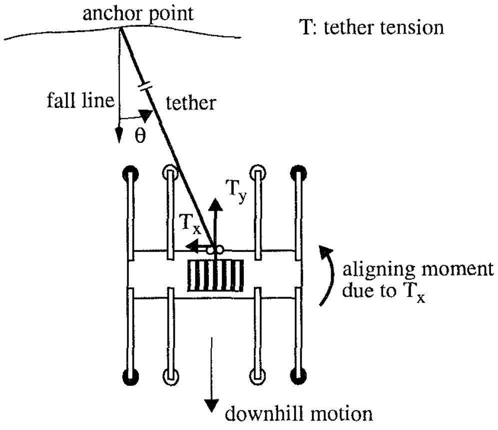

Figure 3: Restoring force (Tx) and aligning moment that act on the rappeller when its path deviates from the fall line

One method of preserving static stability on this class of terrain is through the use of a tensioned tether cable. The tether cable balances a portion of the gravitational force to maintain a suitable stability margin (Figure 2). The tether tension also greatly reduces leg loading parallel to the slope which simplifies leg design and lowers structural weight. However, the tether tension can become problematic when the rappeller deviates from the fall line and a restoring force acts on the body of the robot (Figure 3). Under certain conditions, restoring forces can destabilize the robot and cause roll over. For this reason a rappeller should have significant capability to surmount obstacles in order to sustain locomotion with minimum deviation from the fall line.

Rappelling on extreme terrain involves traversing cross-slopes and slope transitions, conditions that impose tough requirements to the stability and terrainability of the robot. To cope with these terrain situations the robot should have adequate stability margins and three dimensional body motion capability (posturing) that does not compromise structural integrity. To negotiate combined terrain features such as slope transitions covered with boulders, the robot needs to have significant body clearance and be geometrically adaptive to the terrain.

The Dante program focuses on walking robots as the basis for robotic rappelling. Because of discrete point contacts with the ground walking robots can surmount obstacles and adapt to terrain discontinuities. If legs are capable of individual vertical adjustment, the walker can move its body three-dimensionally, independent of the underlying terrain topology. These features make robotic walkers particularly attractive for rappelling. For instance, legged robots can actively adjust body posture to optimize the stability of the walker against moments due to the components of tether tension.

With ground clearance scaled to prominent obstacles in the specific environment, legged robots can rappel on an approximate straight line with minimal need for steering. As a result they can sustain good downhill progress and minimize the danger of interference between the structure and the rappelling cable (i.e. minimize θ in Figure 3).

Rappelling with minimal lateral excursion also mitigates the aligning moment shown in Figure 3. Walking mechanisms can position body-mounted scientific payload over regions of interest utilizing leg motions. Legs can also act as sampling wands by extending foot mounted sensors into gas vents and water ponds.

3 Locomotion configuration for multi-mode control

A locomotion configuration for rappelling can accommodate multi-mode control if it possesses simple and straightforward body frame kinematics, enables incremental and reversible motions [1], improves terrain views and smoothens the ride of navigation and teleoperation sensors.

A simple walking mechanism is one that depends on a few, discrete actuated motions to move the body and adjust its posture. Control simplicity can be enforced by decoupling the primary body motions such as longitudinal translation and heading change. Direct actuation or drives which consist of fixed-axes mechanisms are technical solutions that greatly simplify the kinematics of the robot's propulsion system.

The locomotion configuration should have the capability to move in conservative increments that smooth coordination of longitudinal motion and tether payout. The ability to perform reversible motions is critical to perform rappelling locomotion on unknown terrain where numerous position corrections and body posture adjustments are required. For example, walking through a cluster of boulders demands that the robot continuously test and reverse motions until it finds the most stable positions (footholds) to place its legs. Moreover, reversible motions are needed to allow the robot to replay motions in the opposite order to escape entrapment.

4 Dante II locomotion configuration

4.1 Leg mechanism

Pantograph linkages which amplify hip (guiding point) motion at the foot (following point) by a geometric magnification factor have been used on many of the most successful walking robots [2] [3] [4]. Large vertical foot strokes which can be achieved by use of a pantographic linkage enhance the terrain adaptability of a walker. As a result of motion magnification, significant foot travel can be achieved with small actuator stroke. Figure 4 illustrates the magnification advantage of a simple two-dimensional pantograph in which the guiding point B translates along the vertical axis and the lower guiding point A is hinged. The geometric advantages of a pantograph make it suitable for walking rappelling. Furthermore, leg actuation is performed on the body frame rather than within the leg structure, and therefore the motors and the drives are protected from environmental hazards. The disadvantage of the pantograph configuration is that loads at the foot are multiplied by the magnification factor at the guiding point. Fortunately, the need for a small stroke at the guiding point allows a compact design of the drive system.

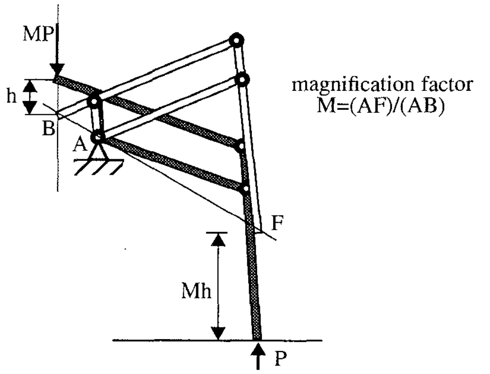

Figure 4: Kinematics of a simple two-dimensional pantograph

4.2 Tethering and leg arrangement for rappelling

Rappellers are biased to generally move up/down slopes due to the fact that the tether is anchored. Tethering configuration relates to the issues of winch placement and tether payout to achieve robust rappelling along the fall line. To maximize the ability of the rappelling walker to actively control tether payout for the purpose of optimizing stability and simplifying motion control, the tether winch is placed on the rappeller instead of being placed at the top of the slope. Moreover, locating the winch near the geometric center results in a uniform distribution of weight and enhanced stability by minimizing the offset between the center of gravity and the geometric center. To encourage kinematic simplicity and similar stability margins, an even number of legs are symmetrically allocated around the winch. The pantograph legs can be arranged in frontal or sagittal configurations [5].

In the frontal leg arrangement (Figure 5), the principal plane of the pantograph is orthogonal to the direction of motion of the walker and orthogonal to the tensioning cable (assuming a straight line descent into the crater). A frontal configuration with two-dimensional pantograph legs was implemented on Dante, the predecessor of Dante II [4]. The frontal leg arrangement proved problematic primarily because of the complexity of coordination control between body propulsion and tether payout. High leg compliance in the rappelling direction deteriorated the precision of motion servoing. Imprecise tether tensioning control led to frequent out-of-plane overloading of the pantographs which caused structural failures.

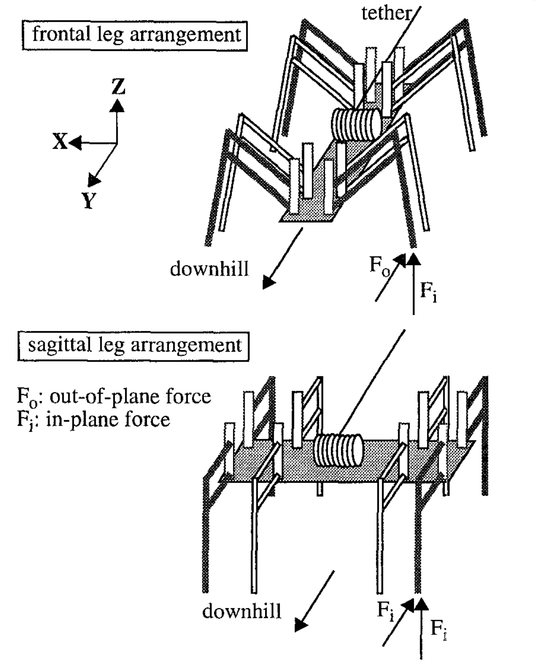

Figure 5: Leg arrangement for rappelling

A sagittal leg arrangement is found to be more appropriate for a robotic rappeller that utilizes two-dimensional pantographs. In this type of arrangement the principal plane of motion of the leg is parallel to the downhill motion of the walker and direction of tether payout. The sagittal configuration fully exploits the kinematic advantage and structural strength of the pantograph. High leg stiffness and strength in the direction of rappelling contribute to more accurate positioning of the mechanism and improved operational safety margins.

4.3 Framewalking actuation of leg groups

Grouped leg locomotion is achieved when certain motions of a set of legs are coupled to the same propulsive or steering actuator. Alternately, the same result is possible by synchronizing certain motions in sets of mechanically independent legs. Leg grouping leads to configurations that have fixed support polygons [6]. Grouped leg walkers with leg sets translated (or rotated) by a single actuator are the simplest, field proven walking mechanisms that achieve static stability on rough terrain in a direct manner without complex stability planning and control [7]. These features make grouped leg configurations suitable for rappelling locomotion. The primary shortcoming of grouped leg walkers is that footholds must be found in sets, which can be quite constraining in extreme terrain. Increasing vertical leg stroke can help to mitigate the difficulty of searching for foothold sets with appropriate geometric relationships.

The consideration of grouped leg propulsion and turning without additional leg loading other than the gravitational components leads to a framewalking configuration topology. Framewalking is the simplest form of walking locomotion known [8] [9] [10]. Framewalking configurations rely on a minimal number of actuators to enable planar body motions. Leg groups are attached to distinct body structures. In the sagittal leg arrangement, two groups of four legs are required to sustain statically stable walking and satisfy the requirement of symmetric leg placement around the winch.

5 Dante II

Dante II realizes an eight-legged grouped locomotion configuration with a three frame topology. The pantographic legs are partitioned into two groups of four, an inner and an outer frame (Figure 6). The lower input point A (Figure 4) of each two-dimensional pantograph is fixed to a frame, but each leg has its own vertical motion actuator that allows the legs to place at different terrain elevations.

The inner frame contains four legs, whereas each outer frame consists of a two distinct structures each containing two legs. A third structure, called the intermediate frame is the interface structure between inner and outer frames. The outer frames translate together along the intermediate frame. The inner frame can only rotate with respect to the intermediate frame. The purpose of the intermediate frame is to decouple longitudinal translation from heading change.

To achieve longitudinal translation the inner frame legs are raised and their frame translates forward. After the inner frame legs are placed on the ground the outer frame legs are raised and move forward. Longitudinal translation is achieved by a single linear stroke actuator which is moves the two outer frames relative to the intermediate frame. The stroke actuator and the associated drives are located within structure of the intermediate frame.

Heading change is achieved by a single turning actuator which moves the inner frame relative to the intermediate frame. Turning is achieved by raising the legs of one frame and rotating the frame while the legs of the other frame are supporting the weight of the walker. The turning frame legs are placed on the ground and the process is repeated with the other frame legs to align with the new heading. The amount of turning that can be accomplished in one cycle depends on the relative dimensions of the frames and the spacing between neighboring legs on the same side of the body.

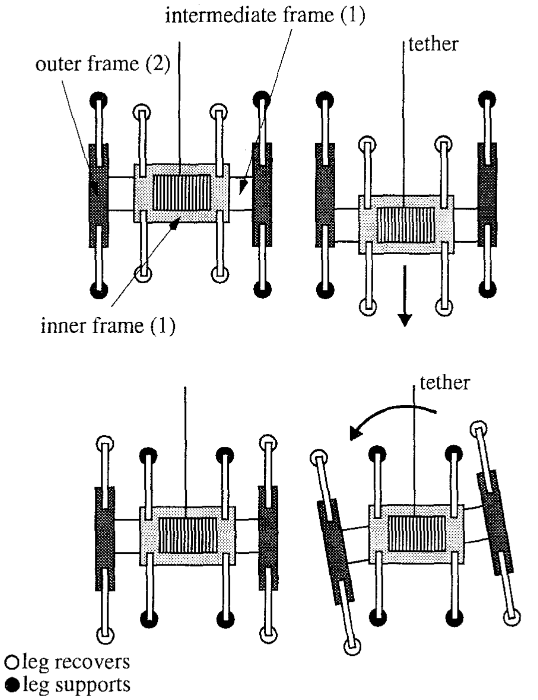

Figure 6: Dante II framewalking motions: translation and heading change

Translational motion is aligned with tether payout by mounting the winch to the inner frame. As a result, coordination control between body translation and tether payout is greatly simplified and can be achieved with only a single force measurement [11]. The tether cable is wound and unwound only when the inner frame moves. During the translation of the outer frame there is no tether payout and the tether cable maintains a prescribed tension. On steep slopes Dante II relies on the actively tension-controlled tether cable to preserve static stability and reduce leg loads in the plane of the pantographs. Body clearance adjustment and three dimensional motions can be achieved by simultaneously driving the vertical motion actuators of the appropriate pantographs.

The robot was equipped with video cameras for teleoperation and a scanning laser rangefinder for perceiving the terrain ahead and around the robot (Figure 7). A virtual reality environment provided views of a three-dimensional kinematic model of Dante II superimposed on an elevation map of the terrain surrounding the robot rendered from the laser scanner data. In conjunction with the simulated displays stereo images obtained from a pair of video cameras on-board the robot were displayed on a stereoscopic monitor and with the aid of special glasses enabled telepresence [12].

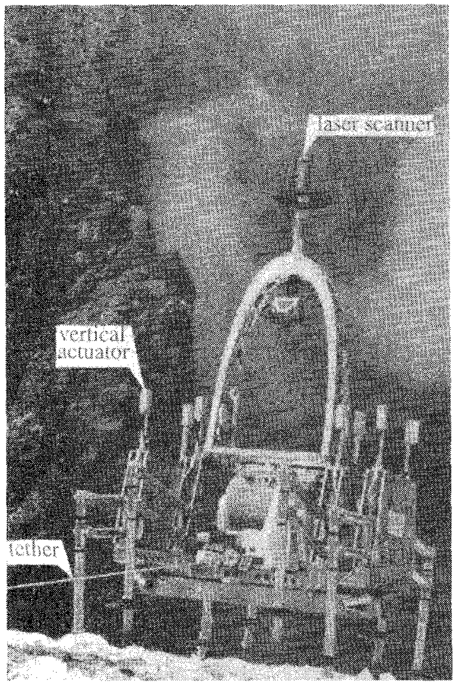

Figure 7: Dante II rappels into the crater of Mount Spurr

6 Performance summary

Dante II underwent extensive testing before its mission to Mount Spurr. Indoor tests on inclined smooth surfaces demonstrated the capability of the walker to perform framewalking rappelling locomotion. Various strategies for executing slope transitions were tested while under human control and direct sight of the robot. These tests revealed the robustness of the sagittal framewalker with two-dimensional pantograph legs to achieve smooth body motion as the robot transitioned through 30^{0} slope changes.

The advantages of the pantograph legs became explicit when the robot was tested in a bouldered field. Both good ground clearance and the ability to place the legs at different elevations were necessary to succeed in this type of terrain. The utilization of four legs per body frame proved to be extremely important in preserving the static stability of the walker when one of the legs slipped off a rock or terrain collapsed beneath it. However, it became evident that group leg stroking and turning limited the terrain adaptability of the robot. In many situations the