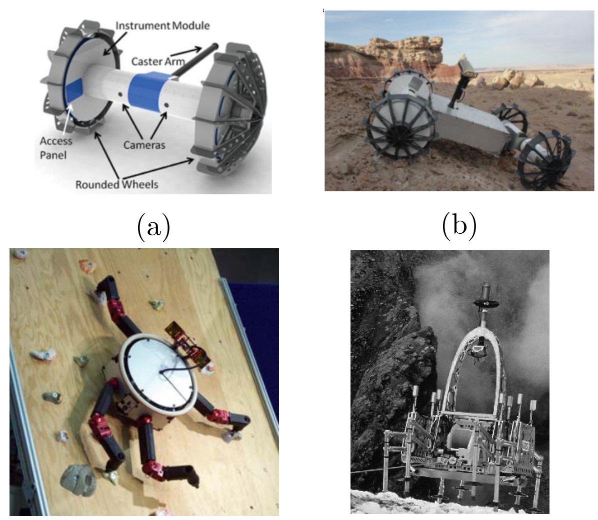
Coordinated Planning and Control for Teams of Tethered Space Exploration Rovers

Motivation: Many important and rewarding science target locations on extra-planetary bodies lie in terrain that is rocky, uneven, or involves traversing steep inclines. Consider the search for ice in underground caves on Mars, or collecting soil samples and images from the bottom of a crater or ravine. These tasks, while very rewarding in terms of scientific value, are not easily achieved by humans nor the current generation of planetary rovers. This shortcoming of current exploratory technology has spurred considerable interest in the development of next generation rover designs featuring a tether that either connects the rover to a static point in the environment [references] or, even more desirably, connects to another rover vehicle of equal capability. A tethered team of space exploration rovers benefits from the stability that a tether can provide while rappelling down difficult terrains. A team also provides added robustness, where the robots can move one to the location of the other to provide assistance. For example, holding robots can reconfigure to provide maximal stability to those descending steep terrain or they can descend down in order to help in case of immobility. Furthermore, robots can swap roles between (1) providing stability to others and (2) traversing the terrain, depending on sensing input. This will allow a tethered team to safely traverse difficult terrain well beyond what a single anchored robot could achieve.

Objective: This report proposes viable solutions for two key and related problems for effective tethered robotic teams. Such progress can significantly improve tethered robot technology for planetary exploration: (a) coordinated control for reconfiguring a tether between a pair of rovers to deal with unforeseen terrain challenges, where both robots actively participate in this process, and (b) a planning framework that utilizes the control strategy as a module for coordinated descent or ascent of difficult terrain for a tethered robotic teams. These solutions should be general enough to be platform-independent and apply to other space critical applications. For example, a tethered team of Robonauts, Valkyries or other humanoid robots could utilize such solutions during a repair mission of the International Space Station.



(a) (b) (c) (d)

Figure 1: (a) The Axel II rover prototype (b) Two Axel II rovers in DuAxel configuration with support structure (c) Lemur IIb autonomous climbing robot (d) Dante II robot exploring a volcanic crater. [references]

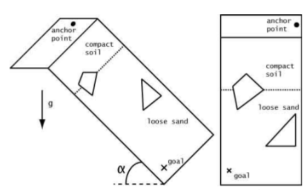
Relevant Background on Tethered Rovers

Recent research into robot designs for the traversal of harsh and difficult terrains has featured several different designs with alternative means of locomotion. Certain systems include an actuated winch or spooled tether used for communication and/or stability while locomoting. Notable examples include an eight-legged walking robot attached to a stationary base [Fig. 1d] and a pair of two-wheeled differential drive robots connected with a soft tether [Fig. 1b]. Even more novel recent robot designs could benefit from the presence of a tether attachment to an exploratory counterpart. This list includes Lemur IIb, a four-legged climbing robot [Fig. 1c], which could potentially use an actuated tether to swing its counterpart onto protruding overhangs and then, in turn, rappel from the stabilized counterpart robot in order to reach the overhang safely.

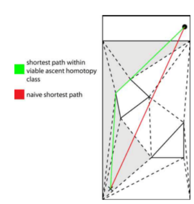
The Dante II robot design consisted of eight legs for locomotion and an actuated winch used for rappelling down steep and difficult terrain from a static anchor point. Both actuation mechanisms were attached to a base frame with a sensor arch protruding from the top of the structure [1]. A variety of sensing equipment, including a pan/tilt camera and a laser range finder, were attached to the arch in order to retrieve and transmit data from remote locations. In 1994 the system was deployed into Mount Spurr, an active volcanic site, in order to record data for further scientific analysis. The robot's control during this time was a combination of supervised autonomous motions and remote teleoperation [2]. During the mission the robot suffered from a failure where the robot incurred a lateral force at its contact point with the tether, fell over, and was not able to correct itself. Apart from this occurrence, however, the 5-day mission was regarded as a success in showing the capabilities of tethered robotic systems to act as "surrogate scientists"; exploring where humans would not otherwise be able.

More recently, NASA's Jet Propulsion Laboratory has been working on a two-wheeled differential drive tethered robot, appropriately named "Axel". The Axel II robot design features collapsible, paddled wheels, making the system more appropriate for longer and more remote missions as this design is more robust to issues such as high-centering and failures such as that encountered by Dante II [3]. The tether mechanism is connected to the axle between the two wheels and is actively spooled as the wheels move relative to the body of the robot. Two variants of the system are presented: one in which Axel is attached to a stationary anchor point, and a second where two Axel robots are tethered together and deployed via a central support beam ("DuAxel") [4].

(a)



(b)



(c)

Figure 2: (a) Conceptualized descent terrain for Axel II mission (b) example projection of terrain to 2D plane (c) example solution: viable controllable regions for ascent (shaded), naive shortest path (red), shortest path within viable homotopy class (green).

A key challenge in either design variation was how to plan autonomous descent and corresponding ascent paths for the deployed, tethered Axel robot in uneven, rocky, extra-planetary terrains. A solution framework was presented which projected this complex problem to a two-dimensional plane. It built on foundational work addressing the tether constraint problem from a computational geometry perspective [5, 6] and extended this approach to produce "controllable" paths by deriving equations of motion arising from the constraints of the Axel robot [7]. The problem addressed in this work was that of planning a single mission, consisting of a descent and corresponding ascent, while being stabilized by a tether attachment to a static anchor point. The resulting algorithm first plans the more difficult ascent path and then uses the solution to limit its search for viable descent paths lying in the same homotopy class.

While this solution represents substantial progress well-grounded in foundational work, the assumptions and simplifications may limit its applicability. In particular, projecting complex 3D terrain environments in 2D and representing obstacles as simple polygons [Fig. 2b] may be not adequate for many realistic extra-planetary terrains. This strategy also assumes perfect prior knowledge of the environment, frictionless interaction of the tether with the ground plane, and quasi-static motion of the robot. Furthermore, it remains an open question as to how best to plan autonomous motions for the DuAxel configuration where two dynamic robots take turns belaying each other.

it seems to me that you are not describing any of the (non-NASA) references that I forwarded you about planning for tethered robots - you didn't find them useful?

Proposed Research

The main goal of this research is to address the problem of planning for tethered teams of exploratory robots, while considering the complexities that arise from realistic three-dimensional terrains. The proposed solution first considers a control strategy for addressing unforeseen obstacles and failures. It then uses this strategy as a module in planning paths for tethered robotic teams, in which the robots alternate between exploring and providing support to their counterparts.

The following discussion will focus on the case of a tethered pair of robots but can be generalized to larger teams. The high-level approach is applicable to varying types of tethered rovers provided that they have a means of: (1) actuating the tether at its contact points with each rover, and (2) measuring the forces exerted on each rover at the tether's contact points. The most similar existing system, which could utilize such solutions, is the DuAxel design, which fits these specifications already. Nevertheless, one can also apply this approach to a pair of Lemur IIb robots free-climbing a vertical and jagged cliff face or even a pair of traditional wheeled rovers descending a steep and rocky mountainside.

<u>Research Problem 1: Coordinated control of a soft tether</u>

Goal: In presence of imperfect terrain information, we require a strategy for dealing with both unforeseen obstacles and unplanned tether entanglements on rocky terrain elements.

In the following, we consider several potentially difficult situations that are likely to arise when planning for a tethered robotic pair under imperfect information about the terrain. In addressing this problem in the full 3D workspace, a strategy is required which can deal with two important potential failure cases. First, while an exploratory rover is moving along its planned obstacle-free path, the tether comes in contact with and becomes entangled on uneven terrain (the "snagging" case). Second, while performing the exploratory role, a rover encounters an unknown obstacle obstructing its planned path, which we'll call the "reevaluation" case (addressed in the planar case in previous, related work [8]).

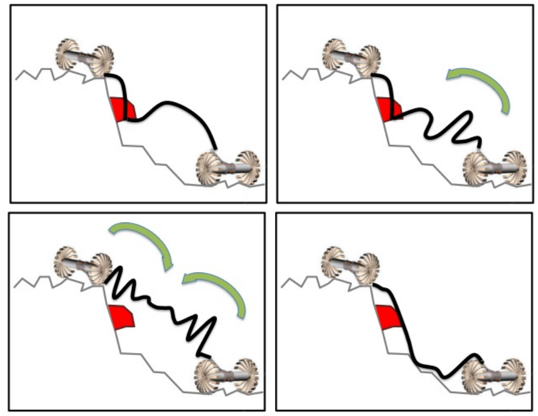


Figure 3: During a coordinated descent down a rocky extra-planetary surface, the tethered rover pair encounters an unplanned snag of the tether with a rock in the terrain (red). The situation is resolved by using the coordinated wave-inducing control strategy (green arrows indicate controls applied) to free the tether.

In the "snagging" case [Fig. 3], we propose to develop a low-level control law capable of inducing a traveling wave in the tether by employing an oscillatory control policy at the actuated tether contact of the rover closest to the tether snag location. This approach is similar to the strategy used by humans when they encounter the same situation while mountain climbing. The challenge in this strategy, however, is that once the tether is free, it's likely to impart a substantial force on the robot's stabilizing counterpart, potentially resulting in dangerous jerking in a partially known environment. A promising solution to this problem would be to induce in response a counteracting wave from the stabilizing rover's actuated tether contact. To this end, the first direction to explore involves building a model (potentially analytically) of the expected forces exerted by the induced wave on the counterpart robot. We would then use this model in the context of a model predictive control approach, where the low-level control policy optimizes its current control with respect to counteracting the incurred force over a finite time horizon of future predictions. The second direction, involves exploring model-free approaches (e.g., designing an admittance controller), as it's possible that reacting to forces incurred is a more feasible solution than accurately predicting them ahead of time.

In the "reevaluation" case of encountering an unmodeled obstacle in our path, what we must first decide is whether or not we can configure our tether such that we are able to place the tether in an arbitrary configuration on either side of the obstacle once we have moved past it. The reason we need to know this before moving forward is that while the unmodeled obstacle may not cause significant problems for our current rover's descent, planning the current stabilizing rover's traversal of the same slope is much more constrained as it does not have a stabilizing tether. Being able to place the tether on either side of the obstacle would then allow us to first plan the descent of the current stabilizing rover (incorporating this new obstacle), and then use the traversing rover to place the tether on the side of the obstacle that is easiest for the stabilizing rover to traverse.

There are two tools available to determine whether this new obstacle is surmountable. By considering the height of the obstacle, we can search for configurations of the tethered pair which raise the tether above the obstacle. Alternatively, it is possible to extend the snagging strategy outlined above – simulating the effects of various parameterizations of our wave-inducing control policies to find one that would be able to surmount the obstacle. If such a policy is found, then it can be combined with a motion plan to move the exploratory rover to the desired side of the new obstacle, terminating the control policy once it has successfully reached the target state.

Research Problem 2: Motion planning for dynamic tethered rover pairs

Goal: Develop a robust motion planning framework for a tethered team of rovers by integrating the control strategy outlined above as a subroutine in cases of environmental obstacles and tether entanglements. This framework can plan the coordinated traversal of difficult terrain while the rovers alternate exploratory and stabilizing roles.

Given incomplete knowledge of the environment, the proposed strategy is to first select a set of maximally stable waypoints throughout the terrain. It is then possible to proceed iteratively and in an alternating fashion, first planning the descent of one of the rover pair to the first stable waypoint, then the other to some next stable waypoint closer to the goal. The waypoints can then be thought of as "role reversal" locations. When unforeseen obstacles (or snags) are encountered, the planning strategy can call upon the control strategy as a module and then re-plan. Importantly, re-planning under this strategy only requires re-computing the path between the current set of waypoints, as opposed to the trajectory of the entire traversal.

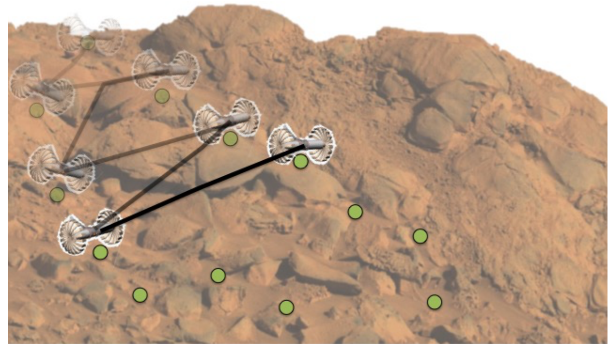


Figure 4: Conceptualized time lapse of coordinated descent of a tethered robot pair. Tether shown in black, computed waypoints in green.

Planning between two waypoints in the full 3D workspace and taking into account the dynamics of the tethered systems can be addressed by using a variety of trajectory-based methods. One promising solution corresponds to sampling-based motion planners, which have been successfully applied to solve similarly high-dimensional problems with complex kinematic and dynamic constraints [9]. A typical limitation with these methods, however, is the relatively high computation requirements to sample enough states to converge to a high-quality solution. Considering that that the objective is to dynamically replan so as to respond to sensing input, an objective of this work is to decrease the amount of time required to find solutions while still addressing this problem in the full state space of the underlying robotic system.

Several techniques can be drawn upon for this purpose. The first set of approaches involve biasing the sampling of states in ways that utilize key aspects of this specific challenge. For example, by computing the "most stable" support position of the stabilizing rover (i.e., perpendicular to the current position of the exploratory rover) and biasing the sampling process toward the subset of the state space with this properties. This work will explore whether or not it is effective to project the problem from the full state space, which may be very high-dimensional, depending on the degrees of freedom of the involved robots, to appropriate lower-dimensional task space projections.

The problem may potentially be dissected into multiple subproblem manifolds, where it may be possible to achieve reliable solutions much faster than in the full state space. In certain cases, this has been achieved through use of machine learning techniques, where it is possible to train a model to learn the important sub-manifolds of a particular system's state space while also learning to predict which static configurations for other state dimensions would be most effective for solving the complete problem [10].

Beyond these research problems:

Describe how you can go from a pair of robots to multiple robots and how this could also be applied to the case of a robot-human team (additional complexities in this case).

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