Planning and Control for Tethered Cave Exploration

Introduction

In this proposal, we consider as an example the case of an exploratory rover which has been deployed into a cave by a main robotic base unit. The tether we consider is a spooled, flexible tether which serves two primary purposes: (1) to deploy into and retrieve the exploratory rover from constrained environments with scientific value in terms of mission objectives and (2) for communication between the exploratory and base units. For the sake of this proposal, we imagine that both rover units at either end have a rotational joint in order to actuate the tether. We also imagine both units to be equipped with a means of sensing forces imparted upon the rovers by the tether (e.g., force/torque sensors).

Research Problem 1: Coordinated maneuvering of a soft tether

Exploring unknown and remote environments such as a cave on a remote planet or satellite involves a substantial amount of uncertainty in the topology of the terrain to be explored. When deploying an exploratory tethered rover into such an environment, the probability of unintentionally wrapping the tether around an obstacle increases substantially **??**. This "snag" in the tether would then impair the robot by reducing its reachable workspace and may render scientific mission areas unreachable.

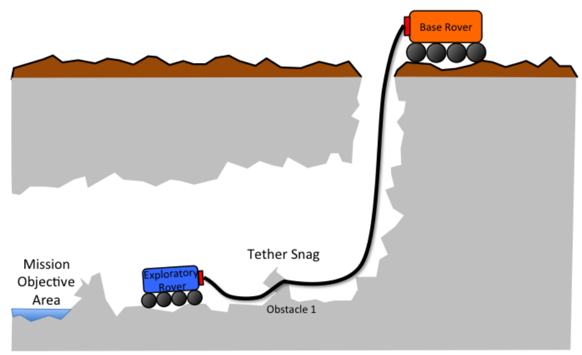

Figure 1: A base rover (orange) has deployed an exploratory rover counterpart (blue) into a cave to achieve scientific mission objectives. Pictured, while in route to the mission objective region, the tethered communications cable becomes snagged on an unknown obstacle.

Addressing this problem in our current example, our first task would be to build a sensing module capable of robustly identifying such situations by using the on-board force/torque sensors and using this information to identify the approximate position of the obstruction relative to the two rovers. In order to then untangle the tether, a promising strategy is to actuate the base rover's tether coupling, producing a traveling waveform through the body of the tether (capable of knocking the tether loose) while simultaneously communicating these controls to the exploratory rover. The challenge in this strategy however, is that once the cable is free it is likely to impart a substantial force on the exploratory robot, potentially resulting in dangerous jerking of the rover in a partially known environment.

We would then propose to solve this problem by propagating in response a second, counteracting waveform from the actuator on the exploratory rover. This would likely involve simulating a variety of such situations in order to build a model of the initial untangling waveform's forces as they are received by the exploratory rover. Using this model, one solution might then be to employ a model predictive control framework which takes as input the control from the base rover and onboard force readings at the tether coupling and optimizes controls to the exploratory rover's actuator in order to best counteract the predicted incoming forces from the tether over a finite time horizon.

Research Problem 2: Motion planning under uncertainty with soft tether constraint

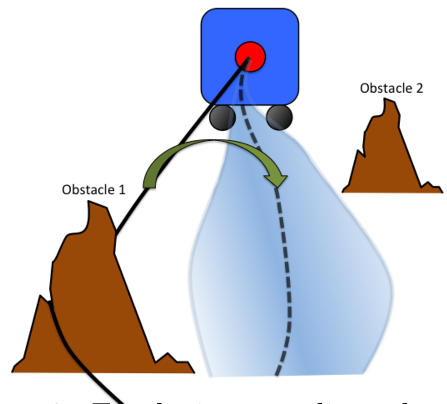

Figure 2: Employing coordinated control between base and exploratory rovers, we are able to relieve the snagged cable (green arrow) but in doing so are left with uncertainty about where the cable now lies (blue region).

Once the tether has been freed from its constrained state, we find ourselves in a better position to achieve scientific mission objectives but likely also are faced with additional uncertainty as to where the tether (and perhaps the rover itself) is actually currently located **??**. This uncertainty necessitates planning over a distribution of current and future states (i.e., planning in belief space), and can best be mitigated by searching for and moving toward observations which most reduce the uncertainty in our distribution over the current state of the robot and tether system. In practice this would likely mean moving toward the edges of our believed reachable workspace (in **??**, to the right of obstacle 2) and using force sensing readings to determine at what point the cable becomes taut against the obstacle.

By first reducing as much as possible the uncertainty in the current state of the rover and that of the cable, we can then proceed to plan in this optimized belief space in order to achieve mission objectives. This problem can be approached in a number of ways. For simple tasks amenable to a large amount of discretization in both the state and observations, we could formulate this as a partially-observable Markov decision process (POMDP) problem and use an efficient POMDP solver. On the contrary, we could employ efficient sampling-based motion planning methods in conjunction with a particle filter in order to operate directly in continuous space. Depending on the complexity of the systems and terrain involved, planning for such a system in belief space could allow for the possibility to leverage foundational work on robotic motion planning with tether constraints on a planar surface, and bring this work into three-dimensional space by, e.g., casting the problem in 2D and using computational geometry solutions to bias our search for feasible motion plans in 3D.