Towards Autonomy and Mobility for a Tethered Robot Exploring Extremely Steep Terrain

by

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Abstract

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Mobile robots are well suited to explore environments considered too costly, time consuming, and hazardous for human inspection. However, a recent push to explore increasingly extreme environments has required the development of robust mobile platforms that can navigate steep, cluttered terrain, operate for extended periods, and relay information to a remote operator. Applications of these systems include terrestrial and planetary geologic survey and infrastructure inspection, where remote observation is not a viable option. This thesis chronicles the design, development, and testing of the physical platform and autonomy functions for the Tethered Robotic Explorer (TReX), a novel mapping robot capable of navigating near-vertical terrain while supported by an attached electromechanical tether; the tether provides continuous power and communication to and from the robot, but also constrains motion due to its finite length and susceptibility to entanglement in cluttered environments. A tethered robot can avoid entanglement by (i) mapping intermediate anchors (locations of obstacle-to-tether contacts), and (ii) autonomously retracing its outgoing path to sequentially unwrap the tether from obstacles. We approach (i) by formulating incremental and batch solutions to a new tethered simultaneous localization and mapping problem using tether measurements to aid odometry and map anchors, and handle (ii) using visual route following in conjunction with autonomous tether control to manage tension and assist the robot to repeat previously driven paths on steep terrain. This work concludes with a geologic surveying mission, where TReX is teleoperated to explore and map a steep, tree-covered rock outcrop in an outdoor mine.

Acknowledgements

"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way" - Charles Dickens (1859)

This excerpt from *A Tale of Two Cities* best captures my experience as a graduate student. From formulating the initial scope of my thesis, struggling through implementation, and finally, demonstrating these ideas in the field, there have been many victories and defeats along the way. The sum total of these experiences, both professional and personal, have indelibly shaped me into a more thoughtful and effective student, researcher, and man. To that end, I want to express my gratitude and thanks to the many people who have helped me along the way. To my advisor, Tim Barfoot, I want to not only thank you for helping me to define the ideas presented in this thesis, but more so, for instilling in me the ability to be my own filter, effectively and concisely communicate my ideas, and of course, to do excellent research. I am sincerely grateful for the opportunity to work with you. To my post-doc advisor, François Pomerleau, thank you for your tireless support, thoughtful advice, and excellent photography throughout the development, testing, and field deployment of TReX. Thank you to my coauthors, Kirk MacTavish for contributing time and ideas to make TSLAM possible, Max Polzin for developing a simple/elegant tether-control strategy, and David Yoon and Tim Tang for your help in lidar-based mapping. Thanks to the rest of the ASRL team, Mike [0], Braden, Katarina, Jon, Chris, Sean, Peter, Mike [1], Kai, Tyler, Mona, Hengwei, and Nan for always lending a helping hand. Thank you to Fulbright Canada for your generous support of my research. Thank you to my friends, family, and sister, Kelly, for treating me like a rock-star/rocket-scientist – it really helped when I needed it most. To Michael, Tom, and Joan, your support is not forgotten, it pushes me forward every day. To my mother, Julie, a life-long cheerleader, thank you for always supporting my crazy ideas and believing in my path. To my wife and love, Tricia Roscoe, thank you for always listening to me and providing endless support and encouragement. Also, thank you for serving as the editor-in-chief on all of my papers (if you find any typos not on this page let her know). Above all, this thesis would not have come together without all of you – seriously.

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Acronyms

TReX : Tethered Robotic Explorer.

TSLAM : Tethered Simultaneous Localization and Mapping.

SLAM : Simultaneous Localization and Mapping.

VO : Visual Odometry.

VT&R : Visual Teach & Repeat.

Notation

a	:	Symbols in this font are real scalars.
$\mathbf{a}$	:	Symbols in this font are real column vectors.
$\mathbf{A}$	:	Symbols in this font are real matrices.
$\mathcal{N}(\mathbf{a}, \mathbf{B})$	:	Normally distributed with mean $\mathbf{a}$ and covariance $\mathbf{B}$.
$\mathbf{1}$	:	The identity matrix.

Chapter 1

Introduction

1.1 Motivation

We are motivated to deploy mobile robots in the investigation of extreme environments considered too dangerous, time consuming, and costly for human exploration. Mobile robots are well suited to access hard-to-reach areas to aid in the geologic survey of cliffs, caves, and crevices, as well as for infrastructure inspection of mines, dams, and buildings. Figure 1.1 provides example applications for robotic exploration in extreme environments. Deploying robots in these environments requires the development of new approaches that extend the current capabilities and autonomy of conventional robotic systems (Schenker et al., 2003). For example, the exploration of steep cliffs on Mars, where geologic history is directly exposed, is well beyond the capacity of currently deployed rovers (Matthews and Nesnas, 2012). Therefore, in this thesis, we address the development of a system that enables a conventional wheeled robot, like those deployed on Mars, to access extremely steep terrain for the purpose of mapping. In particular, we focus on mapping applications that are not suitable for remote or aerial observation, like steep, cluttered areas occluded by structure or vegetation. Moreover, we address the development of autonomy for these systems as a building block towards the autonomous exploration of extreme environments.

A beneficial approach to the exploration of steep terrain involves tethering, which leverages an electromechanical tether attached to a rover to provide support, power, and communication while driving (Wettergreen et al., 1993). We note the important distinction between robots that use tethers as a means of power and communication alone (e.g., underwater robots with neutrally buoyant tethers), and those that additionally exploit the tether's tensile strength for support on steep terrain. Tethering allows a

Figure 1.1: *Exploring the Extreme*: From surveying exposed rock layers on Mars to study formation history, to mapping mine stopes to determine yield, to performing structural inspection, mobile robots are ideal for accessing hard-to-reach areas.

robot equipped with sensors to explore and collect data in normally inaccessible areas for extended periods of time as a result of harnessing off-board power. In comparison, 'untethered' robots (e.g., aerial vehicles), which rely on finite, on-board power, have limited time to map an environment before charging is required. Wettergreen et al. (1993) introduced the first tethered robot capable of exploring steep areas (e.g., volcanoes in Antarctica and Alaska). Huntsberger et al. (2007) and Matthews and Nesnas (2012) provide modern examples of tethered climbing robots for space exploration.

Despite the stated benefits of tethering, the principal disadvantage is that navigation is inherently more complicated; in cluttered environments the tether will come into contact with obstacles and form intermediate anchors (Sinden, 1990). Without careful consideration of anchors, the tether may become entangled and immobilize the robot. The solution to the entanglement problem is two fold: (i) detect and map anchors while driving, and (ii) ensure that the robot retraces its outgoing path in order to sequentially detach from added anchors.

1.2 Research Objectives

The central focus of this research concerns the development of a custom, tethered robot and algorithms formulated to address autonomy in extremely steep, cluttered environments for tethered robots in general. We focus on the following research objectives.

- Systems Design: Enhance tethered robot mobility.

- Tethered Autonomy: Avoid tether entanglement.

- Environment Mapping: Map extremely steep, cluttered terrain.

1.2.1 Systems Design

Drawing on the strengths and weaknesses of prior tethered systems, we have designed and built the Tethered Robotic Explorer (TReX), which is a mapping platform that is capable of managing tether on board and generating 3D scans of the environment. Tether management (reeling in/out) and rotation of an attached 2D lidar are accomplished using a single actuator mounted to a passively rotating tether deployment arm. The tether arm makes TReX unique amongst tethered systems, in that the body of the robot can rotate continuously in place while the arm passively aligns with the current anchor due to tension. This design feature makes it possible to turn on steep terrain and drive tangent to the slope in order to cover/map more area during a single traverse. The tether arm also enables the measurement of the tether's length and bearing-to-anchor, which are used to prevent tether entanglement as explained by the following objective.

1.2.2 Tethered Autonomy

We explore two solutions to the problem of tether entanglement in cluttered environments to enable tethered autonomy. (i) In order to map intermediate anchors, we formulate the first solutions to the tethered simultaneous localization and mapping (TSLAM) problem. In TSLAM, we are interested in estimating the robot's trajectory and map of anchors given nonvisual tether length, bearing-to-anchor, and wheel velocity measurements. While the setup resembles a range-bearing SLAM problem, in TSLAM we must account for the fact that tether length, which can be thought of as a pseudo range measurement, is a function of all anchors contacting the tether, which has implications on the structure of the problem. We show that an efficient solution can still be formulated, as we compare the accuracy of both incremental and batch methods with respect to ground truth using data collected from TReX. (ii) To further reduce the risk of entanglement, we enable TReX to autonomously retrace its outgoing path and sequentially detach from anchors using the idea of visual route following. Specifically, we use the well-tested Visual Teach & Repeat (VT&R) algorithm to backtrack along a set of manually taught paths in both steep and cluttered environments. VT&R relies on a path tracker, which converts localization errors into appropriate wheel actions. However, when the robot loses wheel traction and slips on steep terrain, the path tracker will fail to produce wheel actions that enable autonomous route following. To account for this, we make no modifications to the underlying VT&R algorithm, and instead use a new tether control strategy; the controller selects a slip-minimizing tension, which depends on the vehicle's inclination with respect to gravity, allowing the robot to drive as if it were untethered on moderate terrain and climb steep slopes when wheel traction is significantly reduced (i.e.,tether assistance is required).

1.2.3 Environment Mapping

Finally, we detail a mapping deployment with TReX to investigate a steep rock outcrop at an outdoor mine site in Northern Ontario, Canada. Due to the complexity of the terrain, the robot was manually piloted on a series of steep paths to map a contiguous area with exposed bedrock that spans over 150 meters and is partially covered by forest and ground vegetation. Figure 1.2 illustrates a typical mapping campaign and shows an image from the experiment. The field test served to evaluate both the mapping and system capabilities of TReX. Mapping with TReX involves a 2D lidar mounted on its tether spool, which rotates to generate a 3D scan as the robot drives and deploys tether. Since scanning requires vehicle motion, we must account for scan distortion by estimating the robot's trajectory during a single scan before merging it into the map. Using data collected from the experiment, two existing approaches to handle scan distortion are compared; (i) a continuous-time, lidar-only method that accommodates for asynchronous measurements using a constant-velocity motion prior, and (ii) a camera-aided approach that leverages visual odometry. Once scan distortion is rectified, scans are aligned into a global map of the environment using Iterative Closest Point (ICP) matching. The results include a series of point-cloud maps that are compared to a ground-truth map as well as a discussion of lessons learned from the deployment.

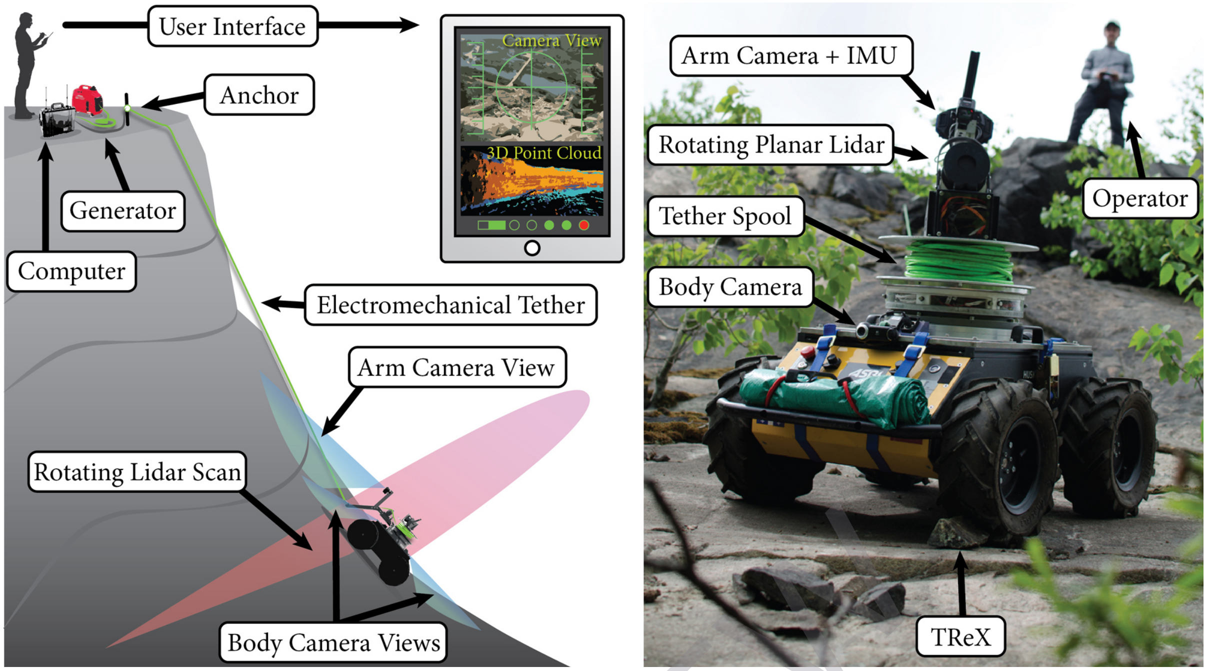

Figure 1.2: *Mission Concept*: The *left* image illustrates a geologic mapping deployment with TReX. The *right* image was taken during an actual field deployment.

1.3 Novel Contributions

This thesis makes the following novel contributions towards robotics research with an emphasis on tethered, mobile systems.

- The first tethered robot design capable of continuous rotation under tension.
- The first formulation of the TSLAM problem with incremental and batch solutions.
- The first demonstration of autonomous route following on steep, cluttered terrain.
- The deployment of TReX to map steep terrain in an outdoor environment.

1.4 Thesis Structure

This thesis is structured to address each of the aforementioned research objectives. First, Chapter 2 details the systems design and initial testing of the TReX prototype. Chapters 3 and 4 address tethered autonomy. Chapter 3 proposes incremental and batch solutions to the TSLAM problem and compares their accuracy on real data with respect to ground truth. Chapter 4 outlines our visual route following pipeline, proposes a tether control strategy, and evaluates results from experiment. Chapter 5 explains the environment mapping pipeline and presents results and lessons learned from a large-scale field test. The structure of each chapter commonly includes a motivation on the topic, a review of prior works, a description and methodology of the system and solution to be evaluated, experimental results validating the proposed method, a list of novel contributions, and references to associated publications and videos. We conclude with Chapter 6, which provides closing remarks, engineering lessons, and proposes potential avenues for future work on tethered systems.

1.5 Associated Publications

The following, first-author papers have appeared for publication and comprise the technical content of this thesis.

- McGarey et al. (2015). System Design of a Tethered Robotic eXplorer (TReX) for 3D Mapping of Steep Terrain and Harsh Environments. In the *2015 International Conference on Field and Service Robotics (FSR).*

- McGarey et al. (2016). The Line Leading the Blind: Towards Nonvisual Localization and Mapping for Tethered Mobile Robots. In the *2016 IEEE International Conference on Robotics and Automation (ICRA).*

- McGarey et al. (2017a). TSLAM: Tethered Simultaneous Localization and Mapping for Mobile Robots. In the *International Journal of Robotics Research (IJRR).*

- McGarey et al. (2017b). Falling in line: Visual Route Following on Extreme Terrain for a Tethered Mobile Robot. In the *2017 IEEE International Conference on Robotics and Automation (ICRA).*

- McGarey et al. (2017c). Field Deployment of the Tethered Robotic eXplorer to Map Extremely Steep Terrain. In the *2017 International Conference on Field and Service Robotics (FSR).*

1.6 Associated Videos

- Intro to TReX: https://youtu.be/Q2gOOhK45lY
- Mechanical Design: https://youtu.be/iQYULj8TLWk
- Building TReX: https://youtu.be/i7e7iHxMmu0
- TSLAM (Particle Filter): https://youtu.be/7ehPxdtYWrA
- TSLAM (Batch Method): https://youtu.be/mzlHJEa3z3Y
- Tethered VT&R: https://youtu.be/qqIkfSabtZs
- TReX in the Field: https://youtu.be/VakpChosVNE
- Mapping Extreme Terrain: https://youtu.be/9r10kC7GTmc

Chapter 2

System Design of TReX

2.1 Motivation

The exploration of steep terrain by mobile robots has been a topic of interest for decades. Prior to the wide-spread adoption of light-weight, energy-dense batteries, many conventional ground robots remained tethered for powering purposes. Even today, due to the limitations of on-board battery storage, roboticists opt to use external power (e.g., an extension cord connecting a robot to wall power) for extended laboratory experiments. Tethering, via an electromechanical tether, is not only ideal for leveraging external power, but also for reliably transmitting data and providing mechanical support on extreme terrain. However, outside of underwater applications where tethering is standard, tethers are not widely used for ground robots because tether management is an unsolved problem in challenging environments (Nagatani et al., 2013). Sinden (1990) first introduced the need for tether management in complex environments as a means to prevent entanglement. Since then, a variety of tethered robots have been developed and tested on steep terrain, but few have addressed tether management as a general problem for mobile robots. Furthermore, a lack of demonstrated autonomy and advanced mobility on steep terrain has slowed both interest and progress in tethered systems. In response, we have developed a new tethered platform specifically to investigate tether management, autonomy, and most importantly, mapping on extremely steep terrain. The Tethered Robotic Explorer (TReX), as seen in Figure 2.1, is the first tethered robot capable of lateral motion on steep terrain while under tension. Additionally, TReX is equipped with sensors that enable tethered autonomy and 3D mapping (see Chapters 3, 4, and 5). In this chapter, we introduce the systems design for TReX, drawing comparisons to prior

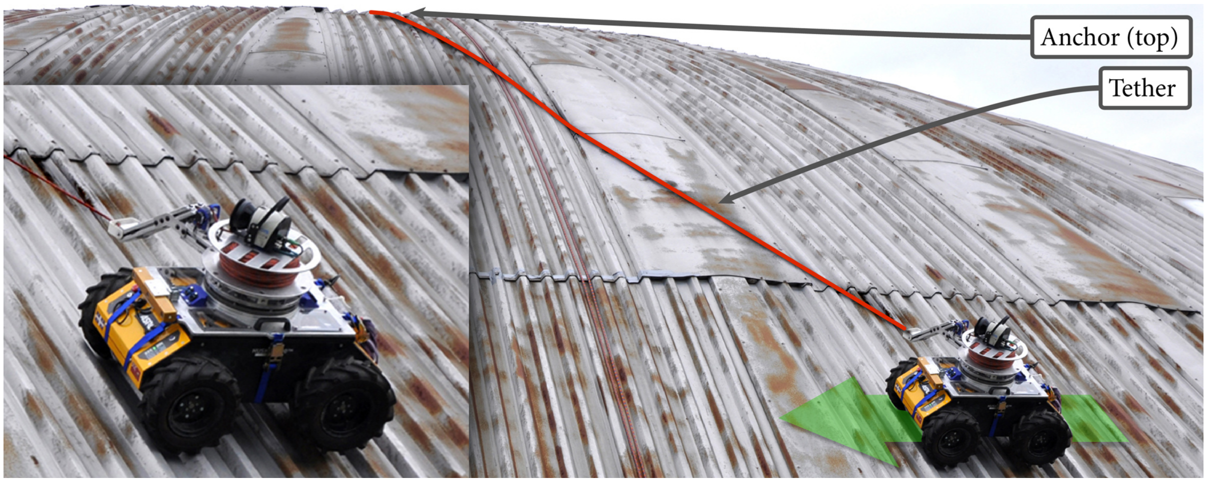

Figure 2.1: *Tethered Robotic Explorer*: TReX traverses the exterior of a dome, demonstrating lateral motion under tension. The heading is shown by a green arrow.

approaches, as well as present results from evaluation and verification of the system.

This chapter proceeds as follows. Section 2.2 presents a brief history of tethered, climbing robots. Section 2.3 details our design and fabrication approach for TReX. Section 2.4 provides results from system verification and calibration tests. Section 2.5 states novel contributions. Concluding thoughts and future extensions for the TReX platform are available in Chapter 6.

2.2 Related Work

Dante I and II (shown in Figure 2.2) were the first tethered climbing systems to be designed and deployed in extreme terrain (Wettergreen et al., 1993). Their unique, eight-legged 'walking' configuration allowed for traversing steep, snow-covered volcano craters and, through testing, demonstrated the challenges of tethered mobility for the first time. During several field deployments, issues related to mobility under tension and tether management resulted in extensive damage to the platform. Following Dante, The Teamed Robots for Exploration and Science on Steep Areas (TRESSA) project outfitted a conventional, wheeled rover with a pair of tethers in order to explore steep slopes (Huntsberger et al., 2007). The dual-tether system provided additional stability, yet made tether management inherently more complex. In fact, tether deployment was coordinated by two separate anchor robots located at the top of a cliff. Additionally, by not managing tether on board, the cables were exposed to abrasion due to dragging,

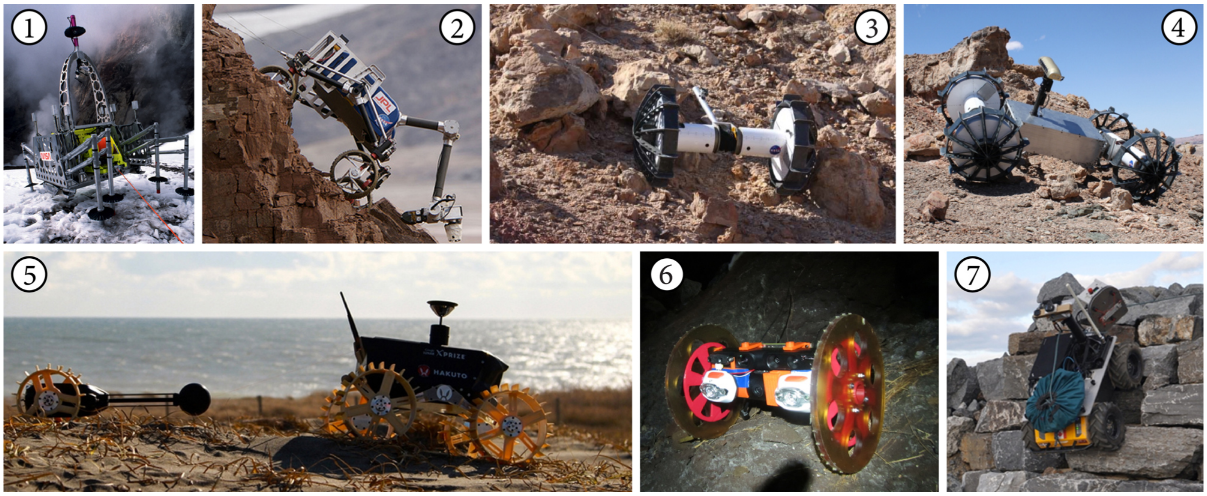

Figure 2.2: *Review of Tethered Robots*: (1) Dante II (Bares and Wettergreen, 1999), (2) TRESSA (Huntsberger et al., 2007), (3) Axel II and (4) DuAxel (Matthews and Nesnas, 2012), (5) Tetris and Moonraker (Britton et al., 2015), (6) VolcanoBot (JPL/CalTech), and (7) vScout (Stenning et al., 2015)

which in turn, decreased the effective range of the robot. More recently, Matthews and Nesnas (2012) developed the Axel robot, which returns to the idea of on-board tether management and uses a novel dual-wheel, self-righting design as shown in image (3) of Figure 2.2. Image (4) shows a variation of the design, which uses two Axel robots to construct a redundant four-wheeled platform, where one of the Axel robots serves as the 'anchor' while the other descends to explore. Axel's design has inspired the Moonraker and Tetris robots (a lunar rover concept from Tohoku University), and VolcanoBot (a volcanic vent mapping prototype from JPL/Caltech), which are shown in images (5-6). The key issue with Axel is that the potential for embedding mapping sensors is limited by design; the current system has a forward-looking stereo camera centered between the wheels with limited space for additional sensors. With the idea that conventional rover platforms are better equipped for sensor integration, the vScout prototype was developed as a precursor to TReX (Stenning et al., 2015). The prototype, shown in image (7), was capable of reeling, but not managing, its tether. The motivation for the TReX design is meant to address a common limitation of all prior systems, which is a lack of advanced mobility on steep terrain; no prior system has demonstrated the capability of turning significantly outside the direction of applied tension to drive laterally with respect to the slope. This disadvantage implies a greater risk of tether entanglement when navigating around obstacles, and also limits the robot to drive in a straight line away from its anchor, which decreases mapping efficiency.

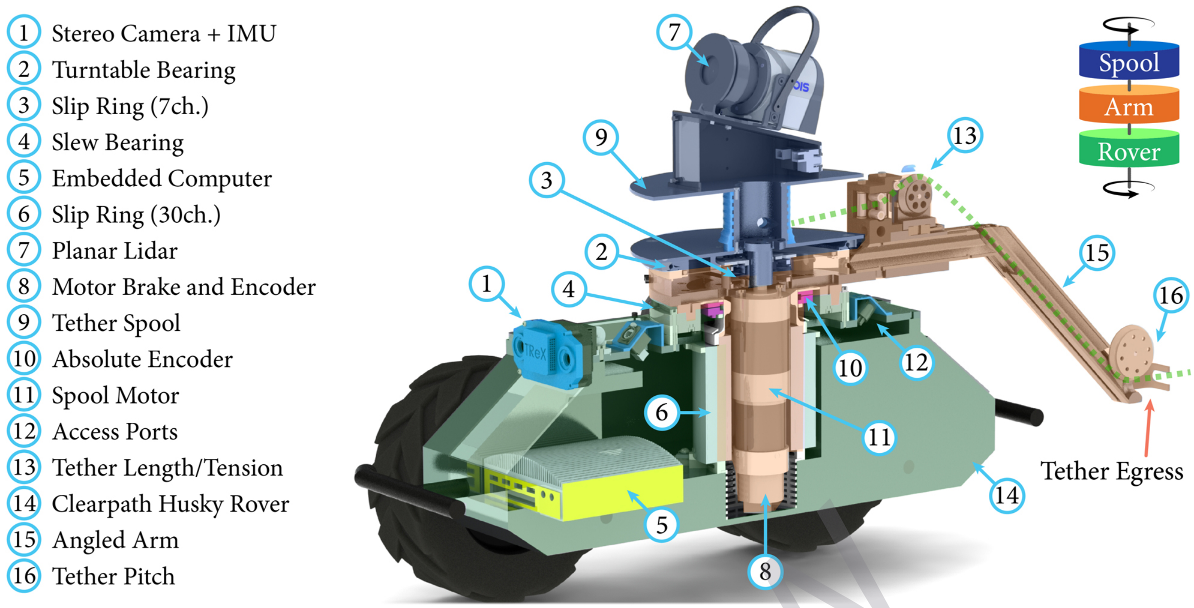

Figure 2.3: *TReX Cut View*: The rotating elements of TReX are highlighted by color. The tether arm (orange) rotates passively in the direction of applied tension. The spool (blue) is actuated with respect to the tether arm. The result is that the rover (green) can rotate in place on steep slopes in order to drive laterally on the steep terrain.

2.3 Design Methodology

2.3.1 Continuous Rotation

In order to navigate laterally on steep slopes, we have developed a tethered robot design that allows for continuous rotation while under tension. The design leverages a tether management payload that attaches to a conventional, wheeled rover and passively rotates about its center (yaw) axis. The payload is mounted to a Clearpath Husky A200 rover, which is a four-wheeled, skid-steered robot base. The tether, which terminates at the rotational center of the robot and tether management payload, is deployed through a tether arm that passively rotates in the direction of applied tension. The tether arm is also angled at the tether's egress point, which has the effect of providing stability on steep terrain by aligning[1] the tensional force with a virtual line passing through the vehicle's center-of-mass. The tether is reeled in and out using a motorized spool, which is not coupled in any way to rover rotation. To visualize the complex rotational freedom of the TReX design, Figure 2.3 provides an annotated cut view with color-coded, rotating elements highlighted. To accomplish the rotation, we have mounted the tether

[1]The tether arm length can be adjusted, i.e., 'trimmed', for better alignment.

management payload on a slew bearing. Power and data are transmitted between the rover base and payload using a multi-channel slip ring with a hollow center. The spool motor is conveniently suspended within the hollow center of the slip ring and is fixed only to the base of the tether arm. Power is transmitted through the slip ring and into the motor in order to rotate a shaft that is coupled to the tether spool. The spool rotates on a separate turntable bearing and is electrically linked to the tether arm by a second, hollow-center slip ring, which allows the motor shaft to pass through. An electronics compartment at the top of the spool distributes power to the top-mounted lidar (light detection and ranging sensor), and is the connection point for the tether. The tether passes AC power and Ethernet data into the electronics compartment. The AC power is used to charge an on-board battery, while the Ethernet signal is linked to an embedded computer located in the rover base. The end result is that TReX can rotate continuously on steep terrain, provided sufficient wheel traction, while the tether spool rotates to manage tension and generate 3D scans using the attached 2D lidar. For more design detail, see the supplemental figures provided in Appendix A.

2.3.2 Comparison to Other Systems

Figure 2.4 compares the mobility of TReX with past systems. TReX's ability to rotate continuously under tension on steep terrain is beneficial for obstacle navigation and efficient mapping. Each platform is evaluated by the following metrics.

- *Rotational Freedom*: Prior systems do not rotate significantly outside the direction of applied tension. TReX has a passively rotating tether arm that allows rotational freedom rotation on steep terrain, provided sufficient wheel traction.
- *Passing Obstacles*: Tether-to-obstacle contacts create intermediate anchors, which must be removed in order for the robot to return safely. TReX has the ability to rotate and drive laterally around an obstacle instead of surmounting it.
- *Climbing Obstacles*: Despite the advanced rotational ability of TReX, there are still challenges to navigating extreme terrain. While Dante and Axel are tailored for navigating over large obstacles, TReX's size and limited ground clearance can cause the robot to get stuck if no alternative path exists around a difficult obstacle.
- *Coverage Area*: The ability to drive laterally on steep terrain allows TReX to sweep back and forth in order to cover more area in a single traverse. Other systems are limited to travel mostly linear paths, which means that the anchor must be relocated in order to cover and map new areas.