Axel Rovers for Exploring Extreme Planetary Terrains

Issa A.D. Nesnas and Joel W. Burdick

Abstract*—Many intriguing science discoveries on planetary surfaces are at sites of extreme terrain topography that are currently inaccessible to state-of-the-art planetary rovers. Exploring such sites is likely to require a tethered rover platform both for mechanical support and for providing power and communication. Mother-daughter architectures have been considered for such missions, where a mother rover traverses untethered for several kilometers from the landing site to a target destination of scientific interest and then deploys one or more tethered daughters across extreme terrains. Deploying and retracting a tethered daughter rover across hundreds of meters of extreme topographies via remote operations from million of kilometers away presents numerous challenges. These include the design of a platform that is robust enough to handle the terrain challenges, the development of on-board sensing and processing capabilities for traversing a range of topographies, and the ability to remotely plan traverses using orbital and on-board sensing and a priori knowledge of the terrain properties. In this paper, we provide an overview of recent research activities and findings that are helping advance our understanding of tethered mobility in extreme terrain. We will describe the salient features of one instantiation of a mother-daughter architecture, the DuAxel/Axel platform, and present results from analysis, lab experiments, and field trials of traversing steep and rocky slopes, scaling cliff face, acquiring in-situ measurements, and collecting and caching samples. We will describe preliminary results from the examination of multiple sampling techniques of soft and hard regolith as well as drilling and coring on slopes. We will describe progress in autonomous vision-based tethered assisted docking and will outline the challenges and progress in tether management and autonomy.

I. INTRODUCTION

A. Mission Architecture

Many intriguing science discoveries on planetary surfaces are at sites that are currently inaccessible to state-of-the-art planetary rovers. Exploring sites such as the seasonal flows of putative brine and exposed strata on crater walls on Mars, cold traps[1] on the Moon, and caves on both the Moon and Mars requires a new class of planetary rovers capable of accessing, loitering and sampling such terrains. Given the extreme terrain topography and, in some cases, the extreme thermal environment, exploring such sites is likely to require a tethered rover platform both for mechanical support and for providing power and communication. Such rovers need to be designed with thermal considerations.

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[1] Permanently shadowed craters within craters in the Lunar polar regions

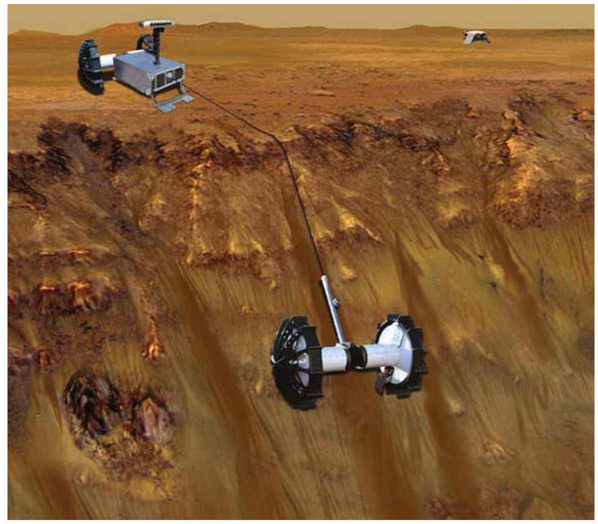

Figure 1. Artist rendition of a mission concept for *in situ* exploration of Recurring Slope Lineae (assets not to scale relative to the terrain)

To explore extreme terrains, a rover must first be delivered by the host mission to a safe landing site on the planetary surface that is in the vicinity (within several kilometers) of an extreme terrain. Such a mission would require at least a 60-day operational period (compared to the 7-day nominal period for Sojourner) to traverse the several kilometers to the extreme terrain before it can demonstrate its extreme terrain capabilities. Mother-daughter architectures have been considered for such missions, where a mother rover traverses untethered for several kilometers to the site of interest, and then deploys one or more tethered daughters across extreme terrains (Fig. 1). Deploying and retracting a tethered rover across hundreds of meters of extreme topographies via remote operations from million of kilometers away presents numerous challenges. First, using a tethered rover to traverse extreme terrains requires a low-mass yet versatile platform to minimize the size of the tether (both for mechanical support and power delivery). Second, the rover platform must to be capable of traversing rocky, steep and very soft terrains and handle abrupt terrain transitions. Third, the rover has to also be able to assess terrain hazards, which are somehow unique for tethered platforms. Fourth, the rover and ground operators have to be able to plan safe route to targets of scientific interest while minimizing risks associated with tether entanglement and abrasion, which is in constant contact with terrains of unknown properties.

A joint JPL and Caltech team has been researching these topics to advance our understanding of extreme terrain tethered mobility in order to retire as many risks associated with the control and operation of these rovers. The team has developed three generations of an extreme terrain rover

Figure 2. (left) Recurring Slope Lineae (RSL) (seasonal flows) in Newton Crater (MRO, HiRISE 2011), (middle) exposed strata in Cape St. Vincent, Victoria crater, Mars imaged by the MER Opportunity rover, and (right) a lunar skylight entrance to a cave or hole (Japan's Kayuga)

prototype called Axel and one DuAxel rover prototype (Fig. 1). In this paper, we will describe the salient features of such an architecture and platform and present results from analysis, lab experiments, and field trials of traversing steep and rocky slopes, scaling cliff face, acquiring in-situ measurements, and collecting and caching samples. We will describe preliminary results from multiple sampling techniques including rock drilling and coring on 65° slopes. We will also outline the challenges and describe progress that has been made in tether management and autonomy.

B. *Mission Relevance*

In January 2012, the National Research Council (NRC) released a report entitled "Restoring NASA's Technological Edge and Paving the Way for a New Era in Space," which identified *extreme terrain mobility* among the top sixteen priorities[2] for technology development for NASA over the next five years [1]. The report prioritized e*xtreme terrain mobility* for NASA's objective to explore the evolution of the solar system and the potential for life elsewhere (*in situ* measurements).

The NRC considered extreme terrain mobility game changing because it provides NASA the capability to maneuver its surface vehicles in extreme terrains in order to "follow the water" (NRC p160) [1]. This was considered a high-priority science focus for Mars and lunar surface missions. The technology would be applicable to human and robotic missions.

Extreme terrain access is a capability that would be relevant to exploration on Earth, the Moon, Mars, Europa, Titan, Venus, and other planetary bodies. However, such access not only requires overcoming the challenges of extreme topographies, it also requires handling other extreme environmental conditions such as thermal and radiation extremes. As such, the immediate focus would be for the Moon and Mars. For Mars, intriguing observations of exposed strata, periodic bedding [2], recurring slope lineae (RSL) (a.k.a. seasonal putative briny "flows") (Fig. 2) all lie in extreme terrains currently inaccessible to state-of-the-art rovers for *in situ* exploration. Such features are hundreds of meters down from the rim and up from the crater floor and are on slopes that are 25°–40°. Based on discoveries of life in extreme environments on Earth, such environments could perhaps be one of the final frontiers on Mars in search for habitable environments. Future investigations would perhaps focus on geological and hydrological characterization of RSL sites. *In situ* analysis and sample capture of outflow deposits that have interacted directly with water on Mars would be responsive to goals of MEPAG [3]. The requirement for liquid water in habitable environments makes the retrieval of outflow samples scientifically important for future return to Earth. Access to exposed strata would provide insight into the composition, structure, and history of Mars.

For the Moon, the Strategic Knowledge Gaps (SKGs) identify the characterization (quality and quantity) of water and volatiles in lunar cold traps, which would require extreme terrain access [4]. The NRC Decadal Survey calls for the development of an "inventory and isotopic composition of lunar polar volatile deposits to understand their emplacement and origin, modeling conditions and processes occurring in permanently shadowed areas of the Moon and Mercury" (page 76 in [5]). A potential investigation for pre-cursor robotic missions would be the exploration of skylights on the Moon and Mars, to evaluate their suitability to serve as temporary habitats for future manned missions and as safe havens from solar flares [6]. Also, for robotic pre-cursor missions, assessing abundance and quality of critical resources, such as water ice (in lunar cold traps), would also be important to follow-on crewed missions. During crewed missions, robotic access to extreme terrain would extend astronauts' reach to more challenging areas within the vicinity of their landing site. The Decadal Survey calls for robotic systems that can be designed to operate in extreme environments deadly to humans, but are programmed and at times tele-operated by humans [5].

[2] The National Research Council revised the 320 technologies identified in the draft set of 14 roadmaps produced by NASA into a structure containing 295 technologies, of which a total of 83 were considered high-priority by the panels. Of the 83 high-priority technologies, the NRC steering committee then ranked and prioritized the 7 or 8 technologies for each of NASA's three objectives resulting in a total of 16 unique technologies that the report recommended to be emphasized over the next 5 years [1].

II. RELATED WORK

Interest in exploring extreme planetary terrains and the development of robots to further our understanding of mobility in such terrains is not new; in fact, it dates back at least two decades. However, some of the aforementioned discoveries and observations coupled with the NRC technology prioritization and recent progress in extreme terrain access and sampling may offer a confluence of events that could lead to a more serious consideration.

Many prior efforts contributed to our current understanding of the potential strategies for extreme terrain robotic mobility. On very steep slopes and cliffs, some type of tethering or anchoring is necessary to provide sufficient forces for stability and maneuvering. A robot using some form of anchoring may provide more flexible maneuvering on steep slopes compared to a tethered robot [7][8]. Nevertheless, anchoring is dependent upon the rock/terrain properties, which are hardly ever characterized *a priori*, increasing the overall mission risk. Alternatively, tethering tends to provide more stability on steep slopes but generally imposes more constraints on the rover motion both laterally and in restricting excursions to lower ground (i.e. lower potential energy). Moreover, such platforms would require active management of their tether, in particular on the ascent, to prevent entanglement and enable consecutive exploration of multiple crater transects. Being able to explore multiple transects compensates for limited lateral mobility.

Different approaches to *in situ* measurements in extreme terrains have been investigated. Some advocated the deployment of a large network of small stationary or mobile sensors that can tolerate the failure of individual units [10][11]. Others considered fewer more capable assets. Robots conceived for extreme terrain access ranged from wheeled, legged, tracked, hybrid, tumbling, hopping and flying robots, several of which were built and fielded. Some have employed umbilicals such as the legged Dante II robot [12] that descended into an active volcanoes and the hybrid legged/wheeled ATHLETE robot that used a tether on slopes greater than 20° [13]. Minimizing complexity, increasing reliability, and being able to access and loiter at designated targets are influential drivers when comparing different approaches. Moreover, designs that reduce power and mass and simplify thermal management fair well for space platforms.

In addition to legged robots, a number of wheeled robots have also been proposed and several prototypes have been built and fielded. A recurring mechanism configuration used a four-wheeled rocker with active suspension to control the center of mass for great stability on slopes. Using such a mechanism, the SCARAB rover demonstrated greater traction with inch-worming maneuvers [14]. Despite this ability to overcome high-slip on slopes, steeper slopes are likely to require an external force, such as the one generated from the use of one or more tethers [15]. In addition to four-wheeled platforms, several efforts have recognized the potential of two-wheel rovers, which appeared as far back as the early 1970s [16][17]. Independently conceived, the family of Axel rovers was initially developed at the turn of the century to provide modularity and separation between the mobility elements that are more likely to fail and the science payloads that are carried by the mobility elements [18]. In 2006, the original Axel rover was retrofitted with a tether and science bays and adapted with grouser wheels for extreme terrain mobility on slopes [20][21].

Figure 3. Axel deploying and acquiring infrared spectroscopic measurements and microscopic images from its instrument bay on exposed strata (40° slope)

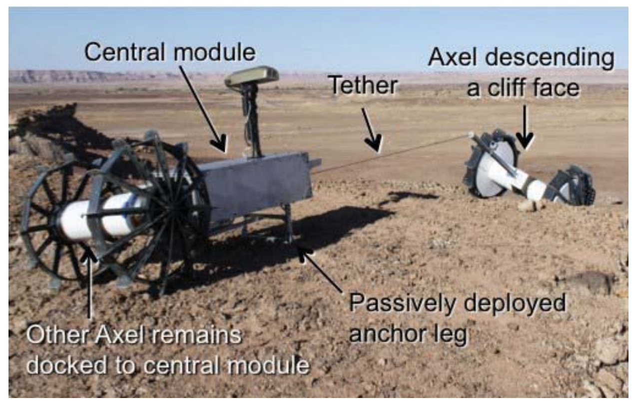

Figure 4. The DuAxel rover with one of its Axels undocking and about to rappel down a cliff face

III. AXEL TETHERED MOBILITY

One realization of the mother/daughter architecture for exploring extreme terrains is the DuAxel/Axel platform. Axel is a two-wheeled rover with two large wheel-encased science bays and a boom (Fig. 3). The boom serves multiple functions: (a) it provides the necessary reaction force on the ground for forward mobility on relatively flat terrains, (b) its continuous rotation around Axel's body provides redundancy for the spool and wheel actuators allowing secondary spooling and straight line driving in case of a failure of any of these actuators, (c) it allows for pointing the instruments, (d) it reduces tether entanglement, and (e) it guides the Axel during the docking process. Using the Axel-mounted umbilical/ tether, Axel is capable of accessing extreme terrains, operating like a yoyo. Using its large grouser wheels, it is capable of traversing obstacles that are a wheel radius in height without the aid of the umbilical. Its symmetric design enables it to operate from an inverted position. The use of an umbilical not only provides mechanical support, but also provides power and communication to the Axel. The Axel rover is unique in that it combines mobility and manipulation functionality into a minimally actuated platform. The science bays on the Axel rover operate in a similar fashion to the arm-mounted turrets on the MER and MSL rover, which are populated with science instruments. A single Axel can carry six to eight science instruments and sampling tools in its science bays. In essence, Axel is a mobile science kit capable of placing and orienting instruments on sloped targets. Fig. 3 shows the Axel rover acquiring spectroscopic measurements and microscopic images of stratigraphic layers on a 40° slope at Black Point Lava Flow in Arizona.

The DuAxel rover is four-wheeled rover with a MER-like mast that carries science instruments and stereo cameras for long-range mapping and navigation of the four-wheel rover. DuAxel is a modular rover that is formed by docking two Axels to either side of the central module (Fig. 4). The central module has two docking hubs, one for each Axel, a power source, likely to be solar panels to trickle charge the Axel through its umbilical, and an anchoring mechanism to ensure stability of the anchor point. Even though the Axel mechanically disengages from the central module, the umbilical remains permanently attached, thus eliminating the risk of unreliable electrical mating in dusty environments. The central module could also carry larger and more sophisticated instruments than the Axels, such as mass spectrometers, to further analyze samples collected by the Axels.

In a typical scenario, the four-wheeled DuAxel rover traverses untethered to an extreme terrain site, such as a crater or a cliff face, and anchors itself at a safe distance from the edge. The two-wheeled Axel rover then undocks from the central module and descends over the edge into the crater. Following its excursion, Axel re-docks to the central module and the now reconstituted DuAxel rover drives to a new site.

While the current Axel research prototypes are at 22 kg (version 2), 40 kg and 55 kg (version 3), a preliminary analysis showed that it is possible to build an Axel rover for a flight mission for as low as 30 kg. That is not an unreasonable estimate given that the six-wheel-drive four-wheel-steering Sojourner rover had a mass of 11.5 kg. A target mass for the DuAxel rover in such a space mission could be as low as 100–120 kg using a single Axel and a central module with permanently attached steerable wheels one the opposite side of Axel, as shown in Fig. 5. Such a platform could fit within the cost-cap of a Discovery-class mission.

In addition to this independent DuAxel rover configuration, a single tethered Axel can also be hosted on a larger rover such as the Mars 2020 rover or a fixed lander to extend its capability with regional mobility. The drawback of such a configuration is that the Axel rover would tie the larger rover operationally during extreme terrain excursions.

Figure 5. De-scope option of DuAxel with a single detachable Axel and fixed front steering wheels

IV. RECENT RESULTS

The Axel configuration with its symmetric design has demonstrated its potential for robust and flexible mobility and operations in extreme terrains. Results from field trails at multiple sites including Black Point Lava Flow in Arizona (Figs. 3 and 4), a mining site in Canyon Country, CA, and at the JPL Mars Yard, demonstrated DuAxel's ability to

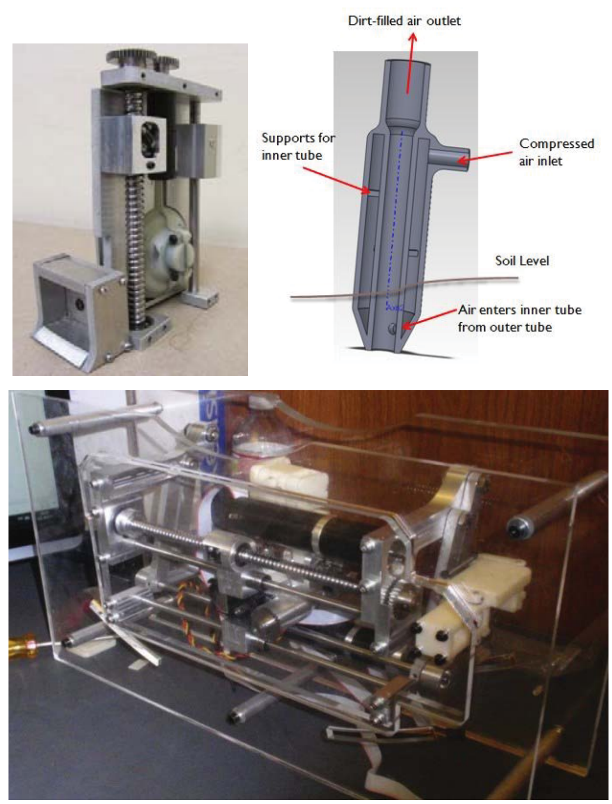

Figure 6. (top left) Percussive scooping device, (top right) design for a pneumatic sampling device for loose regolith, and (bottom) a 4-DOF prototype for a multi-sample scoop, sealing and caching device

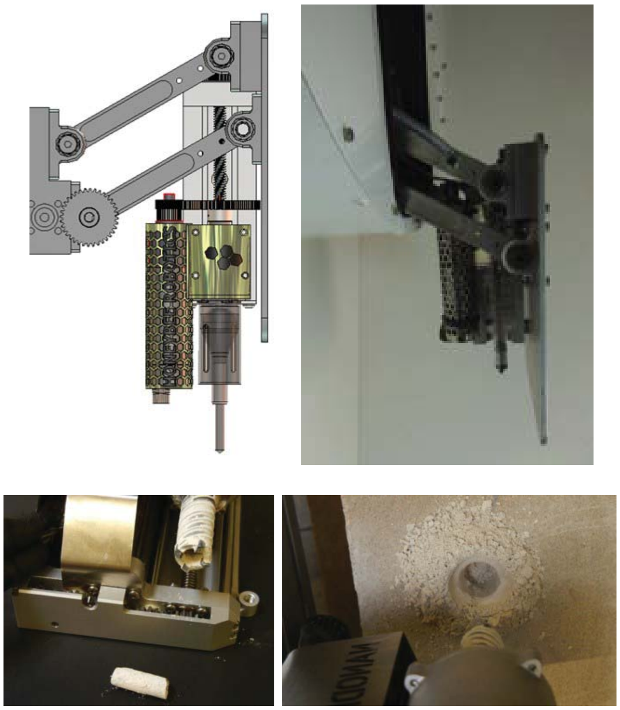

Figure 7. (top left) CAD rendering of the Axel percussive drill, (top right) the actual percussive drill, (bottom left) the Axel coring tool, (bottom right) coring into limestone; both the percussive drill and coring drill were developed by Honeybee Robotics

traverse upslope across rocky terrains unaided by a tether. In one trial at Black Point Lava Flow, the DuAxel rover traversed over a hundred meters to the top of an 8-meter high ledge over rocky slopes reaching 35° in angle. The rover traversed to a location near the edge of the cliff and positioned itself for anchoring. It then deployed the Axel rover, which rappelled over sloped terrain, taking *in situ* measurements on 40°s slopes (Fig. 4) [9]. The rover demonstrated spatially-resolved measurements on exposed strata in extreme terrains in the field including multi-instrument placement on designated targets with an accuracy of less than 1-2 mm. The Axel rovers repeatedly demonstrated rappelling and retracting a tethered payload across distances of up to 50 m (one way) on a range of terrain difficulties with slopes nearing vertical in dozens of runs. All such excursions, however, used direct-view tele-operation.

On-going work includes assessing the ability of operators to achieve the same results for extreme terrain access and measurements using the rover's on-board sensing suite complemented only with orbital-equivalent maps. The Axel rover carries stereoscopic cameras and inertial sensors. Currently, we are investigating an arrangement that uses three cameras in a stereo configuration to provide both short- and long-range stereo using a baseline of 12 cm and 35 cm respectively. Given the low-vantage point of the cameras, the narrow baseline stereo cameras are necessary to reduce parallax distortion for close-up obstacles.

Sampling and sample caching techniques vary depending on the properties of the terrain to be sampled. A group of Caltech students have investigated several sampling techniques on different terrain types. One group investigated pneumatic sampling, sample transfer and caching techniques. A second investigated percussive scooping of frozen ice/sand mixtures, and a third developed a 4-DOF multi-sample scoop, sealing and caching (see Fig. 6). More details on these devices can be found in [24]. In addition, to these investigations, Honeybee Robotics has developed two instruments: a 2-DOF percussive driller with powder caching capability and a 2-DOF coring tool with core break-off capabilities (Fig. 7). Both the Caltech and Honeybee sampling devices were designed to be accommodated inside the Axel science bays. Several have been integrated and demonstrated on in the field on different soil types and rocks.

The Honeybee percussive drill used a 2-DOF rotary percussive drill that collected powdered sample in a hopper at the top of the bit. Table I shows the drill properties. The drill was mounted inside one of Axel's instrument bay and was deployed using the single DOF four-bar deployment mechanism. It successfully drilled into ~45 MPa Briar Hill Sandstone using less than 0.1 Nm, collected the powder sample, and ejected it by reversing the drill bit direction.

TABLE I. HONEYBEE PERCUSSIVE DRILL

Description	**Value**	**Comments**
Auger/bit speed	2020 RPM	
Auger/bit torque	0.50 Nm < 0.1 Nm	Max continuous Nominal
Percussive Energy	~0.013 J/Blow	
Percussive Rate	~39000 BPM	at 2020 RPM auger velocity
Bit Diameter	~4.8 mm	Outer diameter

TABLE II. HONEYBEE NANODRILL

Description	**Value**	**Comments**
Auger/bit speed	225 RPM	
Auger/bit torque	1.41 Nm ~0.6 Nm	Max continuous Nominal
Percussive Energy	~0.10 J/Blow	
Percussive Rate	675 BPM	at 225 RPM auger velocity
Bit Diameter	~11.5 mm 7.5 mm	Outer diameter Inner diameter

A second sampling device from Honeybee Robotics, termed the NanoDrill, used a 2-DOF rotary percussive coring tool that also provided core break-off and retention, and bit retraction capabilities. The device currently uses gravity for core ejection. Table II shows the properties coring device. The drill was also mounted inside one of Axel's instrument bay and was deployed using the single DOF four-bar deployment mechanism. It successfully cored ~45 MPa Indiana Limestone using less than 0.6 Nm torque on 65° slopes. It broke the core off by reversing the motor rotation, which uses a off-center concentric sleeves to shear the core. The device captured and retained the core sample

Figure 8. Autonomous vision-based tether-assisted docking of the Axel rover to the central module.

and later ejected it. Coring in Limestone was demonstrated from the Axel rover on 65° slopes. Both the percussive drill and coring were done autonomously using Honeybee Robotics developed drill algorithms. Further details on these devices can be found in [19].

Deploying and retracting a tethered daughter vehicle requires undocking and re-docking of the daughter to the mother, with the latter being the challenging part. While aforementioned field trials relied on an operator enjoying a bird's-eye-view for the docking maneuvers, our follow-on work investigated vision-based tether-assisted autonomous re-docking of a daughter to its mother. Using fiducials mounted on the mother to improve the reliability and accuracy of estimating the relative pose of the mother/daughter, we developed and field-tested autonomous redocking in the JPL Mars Yard using the Axel rover and central module (Fig. 8). The tether helps the docking process and increases the system's tolerance to pose uncertainties by mechanically aligning the mating parts in the final docking phase. The autonomous docking algorithm was executed on the Axel rover without imposing any requirements on the central module. It used either of the two Axel mounted cameras to detect and correspond the fiducials to an *a priori* model of the central module. It estimate the relative pose using either monocular on the three-dimensional fiducial locations, rejecting outliers from the detection algorithm. Following that, it used a parallel parking motion planner to position and orient the rover to align the boom with the docking station. Throughout the process, the Axel monitors the pose of the central module and manages its tether. If alignment errors exceed acceptable tolerances, the rover would retract and re-approach the central module. In the final docking phase, the rover would use the tether to reel itself in after putting the wheels in free-rotation mode. This helps align the mating parts. We ran a total of 40 experiments and the algorithm achieved an 80% success rate in both firm and loose soils and starting from up to 6 m away and with up to 40° radial angle and 20° relative heading without knowledge of an initial pose. These preliminary results are encouraging and go a long way to help retire risk associated with the autonomous docking process. Since all failures have been characterized, we do not anticipate major difficulties in raising the success rate to the high nineties.

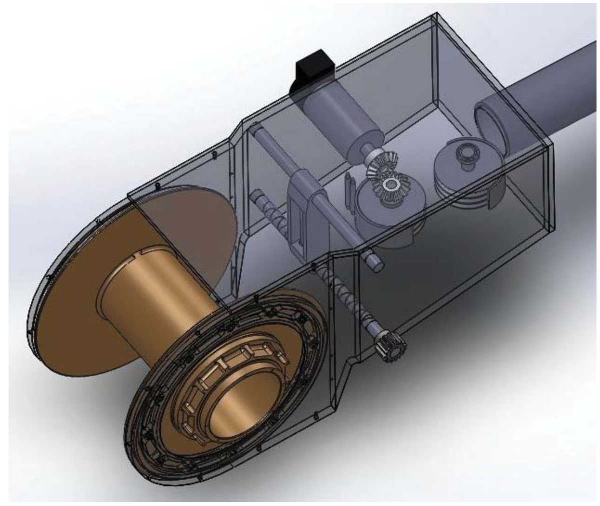

Figure 9: One potential design concept for tether tension reduction and spooling for the Axel rover

V. FUTURE WORK

On going work involves the design of a tether management system that can support the large range of tether tensions (0–750 N) that are typically experienced by the rover during such extreme terrain excursions. We used data from prior field trials to define requirements for such a system. This work involves the development of tether control algorithms to minimize tether abrasion and ensure proper spooling (Fig. 9).

On the mapping and navigation, we continue to develop mapping techniques from the Axel's on-board stereo cameras and terrain hazard assessment. The latter involves a re-examination of hazards for tethered rovers and analyzing trafficability of rovers in extreme topographies that can no longer rely on flat occupancy grid maps. We also continue to develop planning algorithms for long excursions that avoid tether entanglement and minimize tether abrasion.

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