The Axel Marsupial Rover for Challenging Terrain Sampling

Issa A.D. Nesnas[1], Pablo-Abad Manterola[2], Jeffrey Edlund[2], Joel Burdick[2]
[1]*Jet Propulsion Laboratory, California Institute of Technology*
nesnas@jpl.nasa.gov
[2]*California Institute of Technology*
pabloam@gmail.com, jedlund@caltech.edu, wb@robotics.caltech.edu

Abstract

Challenging terrains on planetary surfaces appear to offer some of the most interesting scientific sites to explore and mine for resources. For example, some scientists believe that there is hidden water inside some of the Moon's permanently shadowed craters. On Mars, the discovery of possible spurts of water flow were observed on the inside walls of two craters. Exploring and sampling such locations using robotics vehicles is very challenging. In this paper, we will examine the capabilities of the Axel platform for that purpose. Axel is a minimalist rover that is tethered to its host and is capable of in-situ measurements and sampling on such terrains. We will present some analysis and preliminary results of the Axel rover operating in the JPL Mars Yard on terrains with slopes up to 90°.

1. Introduction

Some of the most interesting sites to explore and mine on planetary surfaces present severe challenges for robotic platforms. Whether it is steep and deep craters on the Moon, potential caves on Mars, or features on the surface of Titan, collecting terrain samples from such sites remains largely out of reach.

In this paper, we will present the concept of a marsupial rover that is tethered to a host platform. We will illustrate how this rover concept extends robotic mobility to some of the more challenging sites on planetary surfaces. Figure 1 shows the overall concept: a rover tethered to a host lander descending into a lunar crater.

In the next section, we will describe the exploration scenarios that motivate this work. In Section 3, we will present related efforts. Section 4 will focus on the approach that we have adopted to address this problem. We will provide justification for the architecture, describe the system design, and present its operational modes. In Section 5, we present some theoretical analysis followed by our preliminary experimental results of testing Axel in the JPL Mars Yard.

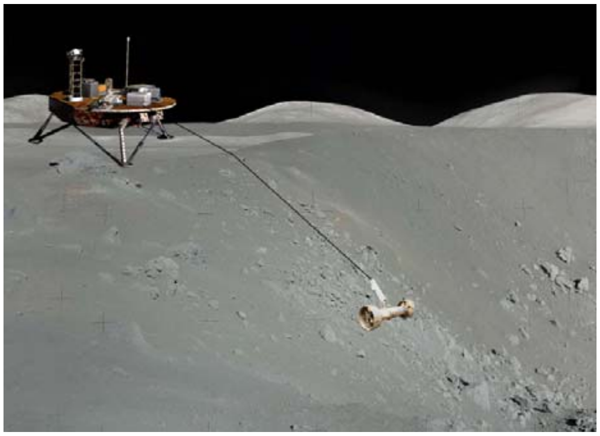

Figure 1. Conceptual rendition of the Axel tethered rover on the Apollo 17 landing site background (picture not to scale)

2. Motivation

Recent missions to the Moon have focused on the search of water ice in the lunar polar regions. The Lunar Prospector spacecraft detected enhanced concentrations of hydrogen close to the northern and southern lunar poles using its on-board neutron spectrometer [1]. Such concentrations were also detected at Shackleton crater. Shackleton crater has been suggested as a potential target for a lunar impactor that will accompany the LCROSS (Lunar Crater Observation and Sensing Satellite) spacecraft to verify the existence of water ice [2]. Shackleton is believed to be a young crater, which indicates that its interior walls are relatively steep for traditional rovers to traverse in search of water ice.

In addition to lunar craters, craters on Mars may also show water activity. The recent discovery of bright deposits in two gullies on Mars suggests possible water spurts. This discovery was made by comparing images taken from the Mars Global Surveyor orbiter over several years. Figure 2 shows

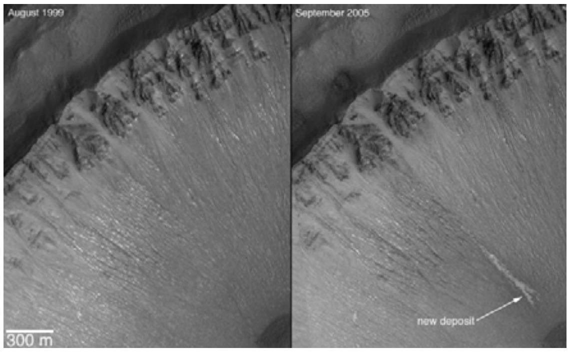

Figure 2. The unnamed crater in Centauri Montes region where bright deposits were discovered

one of the two gullies. The bright deposits were discovered on the inside wall of an unnamed crater in the Centauri Montes region several hundred meters down from the crater rim and on a sloped terrain.

Crater promontories also offer scientifically interesting strata to explore. The background image of Figure 3 shows the Cape St. Vincent promontory of the Victoria crater. The images were acquired from the panoramic cameras onboard the Opportunity rover. The material at the top of the promontory consists of loose rock, which abruptly transitions to bedrock, the top of which is marked by a bright band of rock visible around the entire crater. Scientists have expressed interest in examining these layers of bedrock. For robotic vehicles, this is an extreme terrain with a slippery slope transitioning into a vertical drop overhang that could lead to a vehicle flip over.

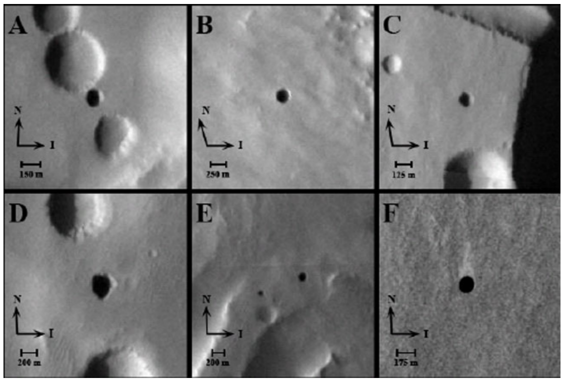

Figure 4. Dark spots believed to be caves observed by the Thermal Emission Imaging System (THEMIS) on the Mars Odyssey spacecraft

In addition to craters, there could also be future interest in spelunking on Mars. The Mars Odyssey orbiter recently imaged seven dark spots near the planet's equator that scientists think could be entrances to underground caves. Caves could become future habitats for astronauts. Figure 4 shows a picture of the potential caves that are near the Arisa Mons massive Martian volcano. Their openings range from 100 to 250 meters wide and with one that is believed to extend to 130 meters beneath the planet's surface.

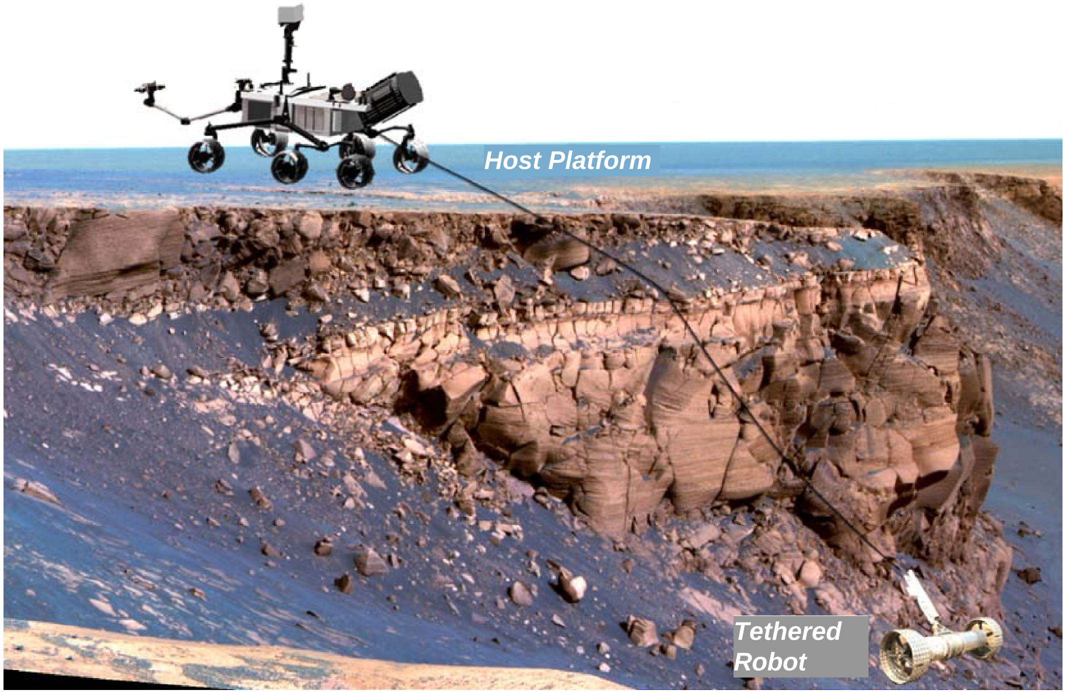

Figure 3. A conceptual rendition of the Axel rover tethered to an MSL-like rover at the Cape St. Vincent promontory of Victoria Crater on Mars (Mars background image has false colors)

In addition to these challenging terrain features on the Moon and Mars, accessing different spots on the surface of the Titan presents an interesting challenge. Balloon concepts are being studied for the potential exploration of Titan. Surface sampling for such missions would require either a descent of the balloon to the surface or a deployment of a tethered device for collecting surface samples. The required functions would include descent, landing, local mobility for better target selection, sample acquisition, ascent, and sample capture by the balloon for science analysis. Such approach for sampling from a balloon has several similarities to that of sampling in caves.

These discoveries have motivated the development of robotic platforms that could access and sample such terrains. These mobility and sampling scenarios are somehow difficult for traditional robotic vehicles. Because of the steepness of the terrain, or its absence in the case of aforementioned balloon and caves sampling scenarios, we use tethered robots. Such exploration scenarios also require a transition between the vertical descent and the surface landing. One cannot predict the landing state of the robot. As a result, it is necessary to design a robot that could either right itself or operate from any stable state.

3. Related Efforts

A few efforts that have used tether robots to explore steep terrains. The most notable example is the Dante II rover [3] that descended into Mt. Spurr crater. Dante II is a four legged frame walker robot that carried a 300 m tether and used an onboard winch to reel/unreel the tether. The winch always maintained tether tension. Care was taken to ensure proper unwinding and winding of the tether. It had a volume of about 3.7 m × 2.3 m × 3.7 m and weighed about 770 kg with an additional 130 kg payload capacity. It used seven video cameras, a scanning laser rangefinder, gas detection sensors, and thermocouples. It could step onto a 1.3 m high boulder from flat ground and was able to rappel down any slope that did not leave it free hanging (<=90). However, it could only handle a 30° cross slope. Its mission ultimately ended when it fell over on its side and was unable to right itself. Such an experience underscores the requirement to be able to operate such rovers in any stable state.

Another tethered rover concept is the Cliff-bot system [9] that uses a total of three wheeled rovers and two tethers to allow one of the rovers to traverse a slope of 70° or less. Two of the rovers act as "Anchor-bots" on top of the cliff and contain winches to control the tethers. The two tethers allow the descending rover ("Cliff-bot") to move back and forth along the cliff face as well as ascend and descend. With a dual tether configuration, cliff-bot unreels the tether from the top of the cliff, thus risking tether breakage through abrasion on the rocky crater rim.

A number of efforts have used designs that allowed the robot to either self-right or operate in any stable state. For example, a team of researchers at the Jet Propulsion Laboratory and California Institute of Technology developed a hopping robot that had wheeled mobility, hopping capability and an ability to right itself [4]. Another robot from the University of Minnesota used a symmetrical design to enable the rover to operate from any stable state. The two-wheeled Scout rover [5] had a small cylindrical body that was a few centimeters in diameter. It was ejected from a cannon mounted on a traditional rover platform. In addition to exploring surrounding areas using wheeled mobility, these cylindrical explorers can hop a few centimeters over small barriers. The concept of minimal actuation for mobility was also used in a commercial two-wheeled robot from Probotics, Inc. [7].

A different steep terrain robot is the STAR four-legged climber [8], which uses ultrasonic drills to create foot-holds in solid rock and other materials. This type of rover could potentially cling to the bottom of an overhanging rock. However, such a system would have difficulty if the slope material were unable to hold its weight. STAR is specialized for climbing. However, because of its legged configuration, STAR is a more complex system with higher power requirements compared to other platforms just presented.

4. Approach

To meet the challenges of the sites presented in Section 2, we designed Axel as (1) a tethered robot connected to a host platform and as (2) a symmetrical robot able to operate in any stable state.

4.1. A Tethered Robot

A tether becomes necessary for reliable and safe operations in challenging terrains. The tether gives the rover its mobility on steep and vertical walls.

Based on the experience of Dante II, placing the tether on the rover would be significantly more reliable despite the additional mass of the cable/winch system. We will later show how we can manage the tether without the need for a winch system in our design. The alternative to carrying the tether on the rover is to

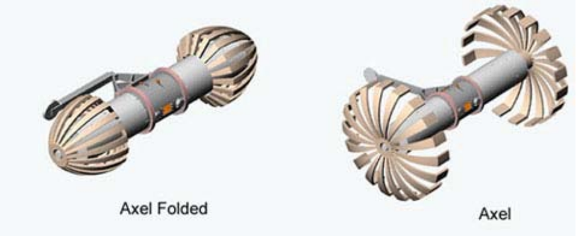

Figure 5. The Axel rover folded in its launch configuration (left), unfolded for surface deployment (right)

reel/unreel the cable from the top. Doing so will subject the cable to severe degradation through the constant shearing of the cable against the sharp edges on the crater's rim, thus risking cable breakage.

The tethered rover concept is designed to operate by landing the mission on the high side of the steep terrain. Operating from the higher potential energy state has several advantages. First, it uses gravity to aid the rover in its descent and uses the cable tension in the ascent. The alternative is to ascend the crater wall from the bottom, which would require firm soil that is likely to be unavailable. Second, it places fewer requirements on the precision deployment of a payload not having to land in a crater. Third, it provides easier access to promontories that are closer to the rim as shown in Figure 3. Fourth, it is the only viable option for balloon sampling and cave exploration.

Therefore, we designed Axel with a single onboard tether. This minimizes the requirements on the host platform to provide only a fixed hook for the tether. Using a single tether has several advantages over multiple ones. In addition to its lower mass, it also reduces the risk of tether entanglement.

4.2. A Minimalist Symmetrical Robot

To operate from any stable state, Axel uses a symmetrical design. Because it is a payload on a host platform, we designed Axel with minimal mass and actuation. For robustness, we designed Axel with minimal complexity. Axel uses differential driving to eliminate the need for complex steering mechanisms.

Axel is fundamentally a two-wheeled rover with a symmetrical body and a trailing link. Figure 5 (left) shows Axel folded in a flight-packaging configuration. Figure 5 (right) shows Axel in its deployed configuration with its large low-inertia wheels ready for surface driving.

One of the primary goals of the design is minimal complexity. Therefore, Axel uses only three actuators to control its wheels and link. The link serves several purposes: it rotates the Axel body relative to the ground, which not only reels and unreels the tether but also adjusts the rover's pitch for pointing its sensors and sampling devices. The link also provides a reaction lever arm against wheel thrust and provides redundancy if one of the wheel actuators fails. The link carries a passive sampling device. Using only three actuators, Axel, is capable of a full range of motions including operating in any stable state, which is necessary when transitioning from vertical free-hanging mobility to terrain mobility. Axel can readily support different wheel sizes and types to support strong impacts.

The co-location of its sensors, actuators, electronics, power, and payload inside the central cylinder simplifies the thermal control of the avionics, which is critical for planetary environments that expose the rover electronics to temperature extremes. In the Axel design, there is no need for wires to go outside the central cylinder thus eliminating the heat loss that would otherwise occur.

Axel runs its tether through its hollow link and uses the link actuator and its cylindrical body as a winch system to reel and unreel the tether. Therefore, it does not require additional actuation. The only requirement on the host platform is a fixed hook for the tether.

The Axel rover was independently conceived in October 1999 [6]. Axel and Scout share several design features due to their minimal configuration. However, Axel has some unique features such as a 360° actuated link that enables control of the rover's body pitch and the tether windings.

4.3. Operation Modes

The alignment of the rotational axes of the three actuators provides Axel with two driving modes. It also provides Axel with redundancy for its drive wheel actuators, where the link actuator can compensate for a failed drive actuator. Free of any tether (or with a very slack tether), Axel has two driving modes: rolling and tumbling. Axel can also operate with a hybrid of the two.

In rolling mode, the wheel motors are actuated to drive the rover. With no tension on the tether, the trailing link rests on the ground. The wheel motor rotation coupled with the reaction from the ground on the link moves Axel in the forward direction. In this mode, Axel's cylindrical body will maintain a constant pitch throughout the motion.

In tumbling mode, only the link motor is actuated, which will then push the link into the ground. The result is a forward motion of the rover. In this mode, the wheels do not move relative to the rover body. However, the entire fixed wheel-body system rotates around the link. This tumbling mode is used to reel and unreel the tether on the rover's cylindrical body. In this mode, Axel has limited maneuverability as it can only move in straight lines forward and backwards.

When driving on slopes a hybrid rolling and tumbling mode is used. Terrain resistance and tether tension govern the switching between these two modes. On vertical walls where there is no terrain resistance or wheel traction, tumbling is the only mode available for mobility.

In rolling mode, Axel is capable of following arbitrary paths: driving straight lines, driving along arcs, turning-in-place, and following continuous trajectories. It can also drive in both directions. When Axel changes driving direction on flat terrain, the lightweight link is first flipped over from one side to the other. Once the link makes contact and provides a reaction force, Axel starts moving in the opposite direction.

To adjust the body pitch of the rover, we drive both the link actuator and wheel drive actuators in opposite directions. The result is a change in the rover's pitch without generating any forward or backward rover motion.

There are two configurations for reeling the tether: clockwise and counterclockwise. It is necessary for Axel to be able to operate with both winding configurations because when Axel transitions from free hanging to sloped terrain, one cannot control which side the rover will face when it encounters the surface of repose. However, the preferred configuration on sloped terrain would be to unreel the tether in the same direction as the slope tumbling direction to enable Axel to roll easily over the rocks.

4.4. Mission Concepts

Axel, basically, operates like a yoyo. For vertical drops such as those from cave openings or for excursions from a Titan balloon, Axel descends vertically by controlling the trailing link. When it encounters a terrain surface, it transitions to a driving mode that continues to unreel the tether.

Axel can be tethered to the gondola of a balloon, a lander, a larger rover (Figure 3), a lunar habitat, or a fixed anchor planted by an astronaut. Irrespective of the host platform, Axel's excursions are quite similar.

In a typical mission scenario, a host platform such as the Mars Science Laboratory (MSL) rover [12] may carry one or more Axel rovers. MSL has payload capability of 65 kg and Axel can be designed with a 5-10 kg mass. In this scenario, Axel will descend over promontory or cliff walls, drive over the rocky crater terrain, reach the soft crater floor terrain, collect soil samples, and reel itself back to the host platform. If an Axel rover encounters regions where it cannot make forward progress, the rover can just reel itself out of that region. The Mars Exploration Rover (Opportunity) was trapped in a soft dune for several weeks in the spring of 2005. In such situations, Axel would be able to use its tether to pull itself out.

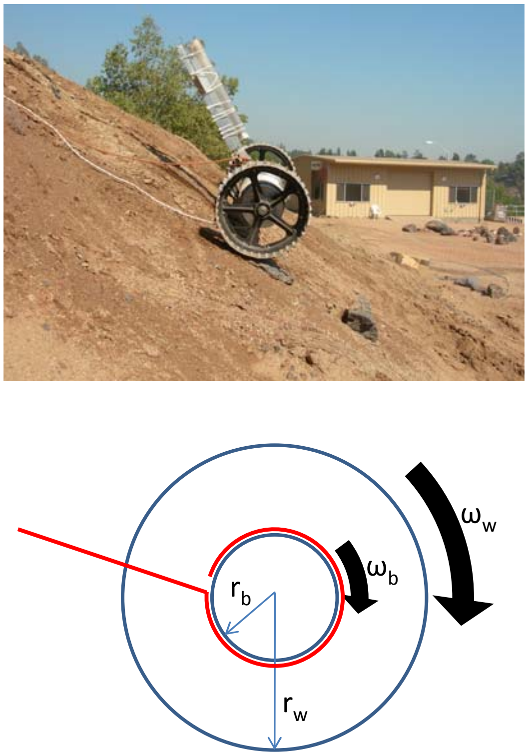

Figure 6. The Axel rover driving down a 40° slope (top). A cross section of the Axel body with the tether winding (bottom)

By separating the sample retrieval rover (Axel) from the host platform, we believe that we can improve overall mission safety by confining the risk of exploring extreme terrain to the smaller rover. For system level redundancy, host platforms can carry multiple small Axel rovers.

5. Theoretical Analysis

In this section, we present a simplified version of Axel's kinematics and dynamics equations that describe the rotation angles, intrinsic forces, and constraints on the rover. Figure 6 shows the tethered

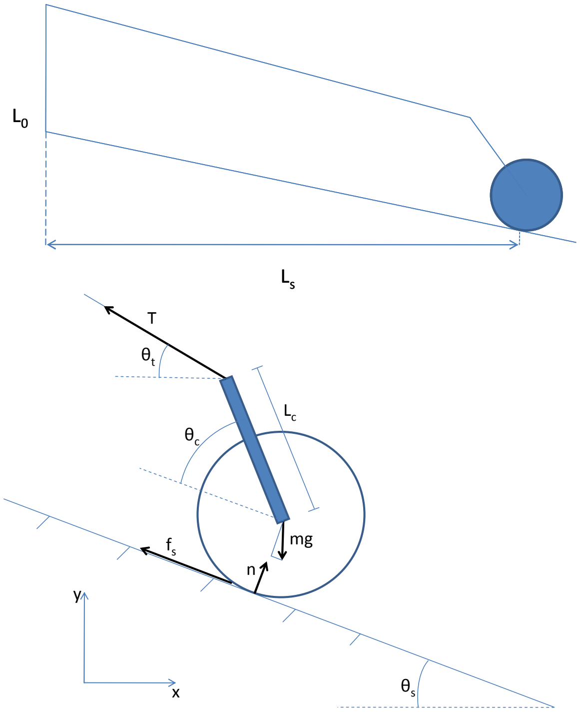

Figure 7. Distance of Axel from the top of the slope (top), free-body diagram of the forces on Axel driving down a slope (bottom)

Axel rover prototype driving down an approximately 40° slope[1].

To properly control Axel's tethered motion on slopes, the rover body needs to turn at a higher rate than the wheels relative to the ground. The ratio of the link to wheel motions is governed by the body and wheel diameters, and is necessary to maintain proper terrain traction without slippage. Figure 6 shows a cross section of Axel driving down a slope. The subscript *b* refers to properties of the body while the subscript *w* refers to properties of the wheel. Thus, for a given body rotation, ω_b, the wheel actuation, ω_{act}, can be computed by [13] :

$$\omega_{act} = \omega_b\left(\frac{r_b - r_w}{r_w}\right) \tag{1}$$

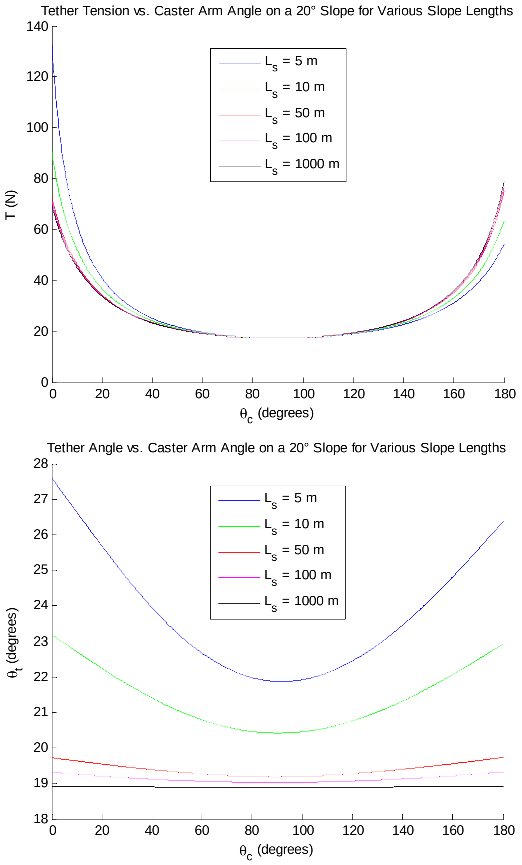

Figure 8. Simulation of tether tension relative to caster link angle and slope length

It is worth noting that since we are assuming the tether is under tension, Axel will travel at speed vb regardless of the wheel rotation speed. This assumption is valid for conditions where the gravity force dominates over the friction force on the wheels, i.e. steep slopes over loosely packed sand. Although the wheels are spinning, the force for motion is derived entirely from gravity (descent) and the tension in the tether (ascent).

Figure 7 is a basic free body diagram for a tethered Axel on a slope of angle θ_s. We will assume that the mass of the body is much greater than that of the link so that the center of mass of the system is not shifted off the axis of rotation. Traveling at constant velocity, the sum of the forces and moments about the center of mass will be zero:

$$\begin{aligned}
\sum F_x &= 0 = -T\cos\theta_t - f_s\cos\theta_s + n\sin\theta_s \\
\sum F_y &= 0 = T\sin\theta_t + f_s\sin\theta_s - mg + n\cos\theta_s \\
\sum M &= 0 = T\cos\theta_t L_c\sin\left(\theta_c + \theta_s\right) \\
&\qquad - T\sin\theta_t L_c\cos\left(\theta_c + \theta_s\right) - f_s r_w
\end{aligned}$$

Since we consider the mass, angles, and lengths known quantities, we have three equations with three unknown forces. After some manipulation, we can express these forces in terms of the known quantities:

---

[1] The steel tether runs through the hollow link coming out of the top end and is barely visible in the picture. The other two slack cables are temporary and are not relevant to the control of the rover. The orange cable is our safety tether. The white cable is a temporary power cable, which will be phased out once we move our batteries on-board the rover.

Figure 9. Axel lowered over a simulated promontory mounted on the viewing platform in the JPL Mars Yard.

$$n = \frac{mg\left(r_w \cos\theta_t + L_c \cos\theta_s \sin\left(\theta_c + \theta_s - \theta_t\right)\right)}{L_c \sin\left(\theta_c + \theta_s - \theta_t\right) + r_w \cos\left(\theta_s - \theta_t\right)}$$

$$T = \frac{mg\, r_w \sin\theta_s}{L_c \sin\left(\theta_c + \theta_s - \theta_t\right) + r_w \cos\left(\theta_s - \theta_t\right)}$$

$$f_s = \frac{mg\, L_c \sin\theta_s \sin\left(\theta_c + \theta_s - \theta_t\right)}{L_c \sin\left(\theta_c + \theta_s - \theta_t\right) + r_w \cos\left(\theta_s - \theta_t\right)}$$

A simplified analysis of the tether tension can be conducted in the case where Axel is either stationary or moving at a constant velocity. We can see from the previous equations that the tension depends on the physical rover parameters, the ground slope, the tether angle, and the caster angle. For various caster configurations, one needs only to compute the tether angle in order to determine the tension. Given a cliff overhang of length L_o and a slope of length L_s, the tether angle is given by:

$$\theta_t = \tan^{-1}\left(\frac{L_o + L_s \sin\theta_s - r_w \cos\theta_s - L_c \sin(\theta_c + \theta_s)}{L_s - L_c \cos(\theta_c + \theta_s) + r_w \sin\theta_s}\right)$$

From the plots in Figure 8, we can see that the tension increases sharply for small caster angles on short slopes and that it reaches a minimum near 90 degrees. Furthermore, the tension at small angles is decreased over longer slope distances.

Figure 10. Axel driving down a 40° rocky slope in the JPL Mars Yard

6. Experimental Results

Our Axel hardware prototype is shown in Figure 9. It has a body diameter of 15 cm with 33 cm diameter wheels. This prototype currently has wheels with a diameter that is 50% smaller than what we desire. This prototype carries a 35 m tether, which runs through the hollow link. The link extends to 70 cm from the center of body cylinder. The tether is a 1/8 inch clear-vinyl coated 7x7 stranded steel fiber cable rated for 920 pounds. Axel weighs about 22 kg including 1 kg for the 35 m tether. Axel is also equipped with stereo vision for obstacle detection and avoidance but that is not used in these experiments. It is currently powered through an external power supply.

A sampling device is mounted alongside the link. The device is a simple passive cylinder with an inset funnel at the far end of the link. The funnel traps soil samples in the caching cylinder. With this device, we were able to collect samples from multiple sites.

We have conducted a series of experiments with the tethered Axel rover using tele-operation in the JPL Mars Yard in the summer of 2007. Tests were conducted on various slopes with different ground types. We have conducted around fifteen runs on a 3 m relatively flat stretch of 15°-20° slope made up of packed dirt. Another eight runs were conducted on a 5 m slope varying in inclination from 0 to 40 degrees shown in Figure 10. These experiments took place on terrain made up of loosely packed sand on undulated slope sprinkled with a number of medium sized rocks (1/3 wheel diameter). Excursions ranged from 10 – 25 m round trip and included several maneuvers on the slope to verify Axel's capabilities. These included manually avoiding hazardous rocks, turning in place while on a tether, arc driving, driving in both directions, and sampling. These maneuvers where carried out on both sloped and flat terrain with a taut and slack tether respectively.

The tests on all slopes were successful--Axel managed to descend on steep slopes, collect soil samples (about 40 g per scoop) and ascend the steep terrain over rocks that were approximately 1/3 of the wheel diameter. Both single samples and multiple samples were collected at various incline points in a single run but the samples were stored in the same sample-caching cylinder. Because our sampling device was targeted for sloped terrain, collecting samples on flat terrain with such a device proved difficult. Collecting samples was very successful on all slopes greater than 10°. Sampling at two different locations during the same run, was neither more nor less difficult than single stage if both testing locations met the minimum slope requirement.

We also conducted experiments to simulate a descent from a promontory, cave or balloon. Figure 9 shows Axel in a free hanging state after descending from an overhang. Because the rover can freely twist on the tether, the rover can end up face up or down relative to the tether winding. By reeling and unreeling the tether through link actuation, the rover was able to raise and lower itself in a stable and controlled fashion without requiring any surface contact.

During these experiments, we encountered a few systematic failures of the current avionics that caused the on-board processor to reboot. This situation occurred a few times during the final ascent stages on a vertical wall with a large rock overhang. We believe that the un-chamfered link could have been caught on a rock crevice. Under such conditions, the CPU would sometimes reboot resulting in loss of control of the rover and engaging of the safety tether. We hypothesize that an overhang impediment resulted in the motors drawing excessive current, which in turn caused a decrease in current flow to the CPU. Further investigation would be required to determine the true nature of this failure and find a solution.

7. Summary

Future surface exploration of the Moon, Mars, and Titan would present some new challenges for robotic mobility and sampling. In this paper, we have examined a new robotic platform for mobility on challenging terrain: steep slopes and overhangs. We have demonstrated the ability of a simple rover design to successfully access and sample on steep slopes. We have conducted over two dozen experiments in the JPL Mars Yard driving the rover over the steepest slopes, collecting samples and ascending back over a simulated promontory. We have demonstrated Axel's ability to descend a 90° hard-packed terrain, transition to very soft sand on steep terrain, collecting samples and ascend back over a simulated promontory. Samples of about 40 g of soil were collected. All experiments were carried out using tele-operation of the Axel rover. Axel holds some promise to extend NASA's mobility to challenging terrain using a low mass mobility platform.

8. Acknowledgments

We would like to thank the team responsible for the original (1999) Axel implementation: Dan Helmick, Prof. Ayanna Howard, Prof. Raymond Cipra at Purdue University, Prof. Murray Clark at Arkansas Tech University and Ed Barlow and students: Raymond Christian, Damon Sisk, Isaac Vaughn, Samuel Irwin, Chad Kessen, and Lauren Lyons.

Additionally, we would also like to acknowledge the support of Prof. Chris Adami of Caltech and Dr. Neville Marzwell, Dr. James Cutts, Dr. Samad Hayati, Dr. Richard Volpe and Dr. Gabriel Udomkesmalee.

This work is a joint collaboration between California Institute of Technology and the Jet Propulsion Laboratory. The work was done at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

9. References

[1] Feldman, W.C. (1998). "Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles". *Science* 281 (5382): 1496.

[2] http://lcross.arc.nasa.gov/mission.htm

[3] J. Bares, D. Wettergreen,"Dante II: Technical Description, Results and Lessons Learned," International *Journal of Robotics Research*, Vol. 18, No. 7, pp. 621-649, July, 1999.

[4] E. Hale, J. Burdick, and P. Fiorini. 2000. A minimally actuated hopping rover for exploration of celestial bodies. *IEEE International Conference of Robotics and Automation*. April 24-28. San Francisco.

[5] Stoeter, S., and Papanikolopoulos, N.P., "Kinematic Motion Model for Jumping Scout Robots", IEEE *Transactions on Robotics and Automation*. Volume 22, No. 2, April 2006, pp 398-403.

[6] I. Nesnas, “Reconfigurable Exploratory Robotic Vehicles,” *NASA Tech Briefs*, Jul 2001.

[7] http://www.probotics.com

[8] M. Badescu, X. Bao, Y. Bar-Cohen, Z. Chang, B. E. Dabiri, B. Kennedy, S. Sherrit, "Adapting the ultrasonic/sonic driller/corer for walking/climbing robotic applications," *Proceedings of the SPIE*, Volume 5762, pp. 160-168, 2005.

[9] P. Pirjanian, C. Leger, E. Mum, B. Kennedy, M. Garrett, H. Aghazarian, S. Fanitor, P. Schenker, "Distributed control for a modular, reconfigurable cliff robot", Robotics and Automation, 2002. *IEEE Int’l Conf. on Robotics and Automation*, Vol. 4, pp. 4083-4088, 2002.

[10] A. Howard, I.A. Nesnas, B. Werger, D. Helmick, "A Reconfigurable Robotic Exploration Vehicle for Extreme Environments," 10th *International Symposium on Robotics and Applications*, Seville, Spain, June 2004.

[11] D. Bickler, “A family of planetary vehicles,” *Proc. of the Intern. Symp. on Mission Technologies and Design of Planetary Mobile Vehicles*, France, 1992.

[12] http://mars.jpl.nasa.gov/msl/overview/

[13] I.A. Nesnas, P. Abad-Manterola, J. Edlund, J Burdick, “Axel Mobility Platform for Steep Terrain Excursions on Planetary Surface, “ *IEEE Aerospace Conference,* Big Sky Montana, March 2008