

On the Design of the Axel and DuAxel Rovers for Extreme Terrain Exploration

Jaret B. Matthews
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-7368
jaret.b.matthews@jpl.nasa.gov

Issa A. Nesnas
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-9709
Issa.Nesnas@jpl.nasa.gov

Abstract— The solar system’s most scientifically tantalizing terrain remains out of reach for traditional planetary rovers, which are typically limited to driving on slopes below 30 degrees. This paper details the design of a novel robotic explorer that would open access to these previously inaccessible locales, such as Martian crater walls where evidence of salty water was recently detected, Lunar polar craters where evidence of water ice was detected, and Lunar and Martian lava tubes for future habitability. The Axel rover is a two-wheeled robot capable of rappelling down steep (even vertical) slopes supported by a tether. The DuAxel rover is comprised of two Axel vehicles docked to a central module. Unrestricted by tether length, this four-wheeled system would be capable of driving long distances from a safe landing zone to the extreme terrain of interest. Once in the vicinity of terrain in which the tether would be required, one of the Axel rovers could undock from the central chassis and rappel downslope. The other Axel and central chassis would remain topside to act as an anchor and to provide line of site to Earth (for communications) and the Sun (for energy). As the detached Axel descends into the area of interest, it would receive power and relays data through conductors in its tether. Each Axel would carry a suite of instruments in a bay that would be tucked inside the wheels. Because of the novel configuration of Axel’s major degrees of freedom, these instruments could be precisely pointed at targets at any desired downslope spatial separation. These instruments could then be deployed into close proximity to the ground by means of a simple mechanism, allowing for detailed study of the strata on the slope. Axel could accommodate a host of instruments, including a microscopic imager, infra-red spectrometers, thermal probes, and sample collection devices. This paper will describe the design of both the latest generation of Axel and DuAxel systems and their instrument/sampling mechanisms. Results from recent field trials at a rock quarry in California and a Martian analog site in the desert of Arizona will be described.

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1. Introduction

State-of-the art planetary rovers (such as the Mars Exploration Rovers or Mars Science Laboratory) are incapable of providing direct access to some types of topographies that are of keen interest to planetary scientists. Instead, these rovers must rely on gravity and luck to bring samples in the form of fallen debris from steep inaccessible terrain into relatively benign and traversable areas. Scientists must then attempt to identify from which layer (and therefore when in history) the displaced rocks originated. This process is difficult and ultimately less satisfying than seeing strata first hand in an outcrop. In addition, there are other regions in the solar system, such as lava tubes and pit craters, which could only be accessed from the top. Conducting any in-situ science at all at these locales would require tackling slopes approaching vertical.



Figure 1 – Artist’s rendering of the MSL rover picking through the jumbled debris from a nearby outcrop

While previous missions rightly decided to go after the low-hanging/fallen fruit first, it is clear that the future of planetary exploration would demand access to ever more challenging terrain. To enable this new, bolder era of exploration would require the development of novel mobility systems that would not be as limited in their ability to tackle difficult terrain. To this end, the Jet Propulsion Laboratory has recently advanced the development of the Axel and DuAxel rover systems via its internal Research and Technology Development Program.

The two-wheeled, tail-dragging Axel rover was conceived at JPL a decade ago as part of a modular robotic concept that used minimalist robots to transport different payload modules to disparate locations for science investigations. In the original concept, the Axel robots served as independent transporters that docked to either side of a payload module allowing the intermixing of mobility and payload components (Nesnas, 2001)(Howard et al, 2004). In 2006, the Axel rover was adapted with a tether for rappelling down steep terrains, turning the original modular robot concept into a platform for extreme terrain exploration (Nesnas et al., 2007).

The two-wheeled rover concept is attractive in its minimalism and symmetry, in that it requires as few as two primary actuators and can be completely inverted without being immobilized. In this recent phase of development, the team focused on designing a platform capable of carrying, pointing, and placing numerous science instruments as well as improved management of its electromechanical tether. This development also targeted the demonstration of the DuAxel rover concept. The DuAxel system, seen in the following figures 2 and 3, is comprised of two

independently operable Axel rovers docked to a central module.

In the nominal Axel surface operations scenario envisaged, a lander deposits a DuAxel rover system in relatively benign (within the safe envelope of the current entry, descent and landing capabilities) terrain a safe distance away from a primary science target located, say, on an extreme slope. The DuAxel system can then make its way as a four-wheeled rover to the edge of the area of interest (i.e. the rim of a crater or top of a fluvial canyon wall). In this mode, the tethers and therefore range of each of the two Axels remain unconsumed. Having arrived at the rim, the DuAxel deploys a leg that anchors it to the ground and provides stability. Subsequently one of the Axels undocks and precedes to lower itself into the extreme terrain. The DuAxel remains on top, in view of the Earth and/or Sun, where it can acquire energy and relay communications to the descending Axel via the tether.

In the following sections, the detailed system design of the latest generation of Axel rover will be described. In addition, the results of two successful field trials of the DuAxel and Axel rovers will be discussed.

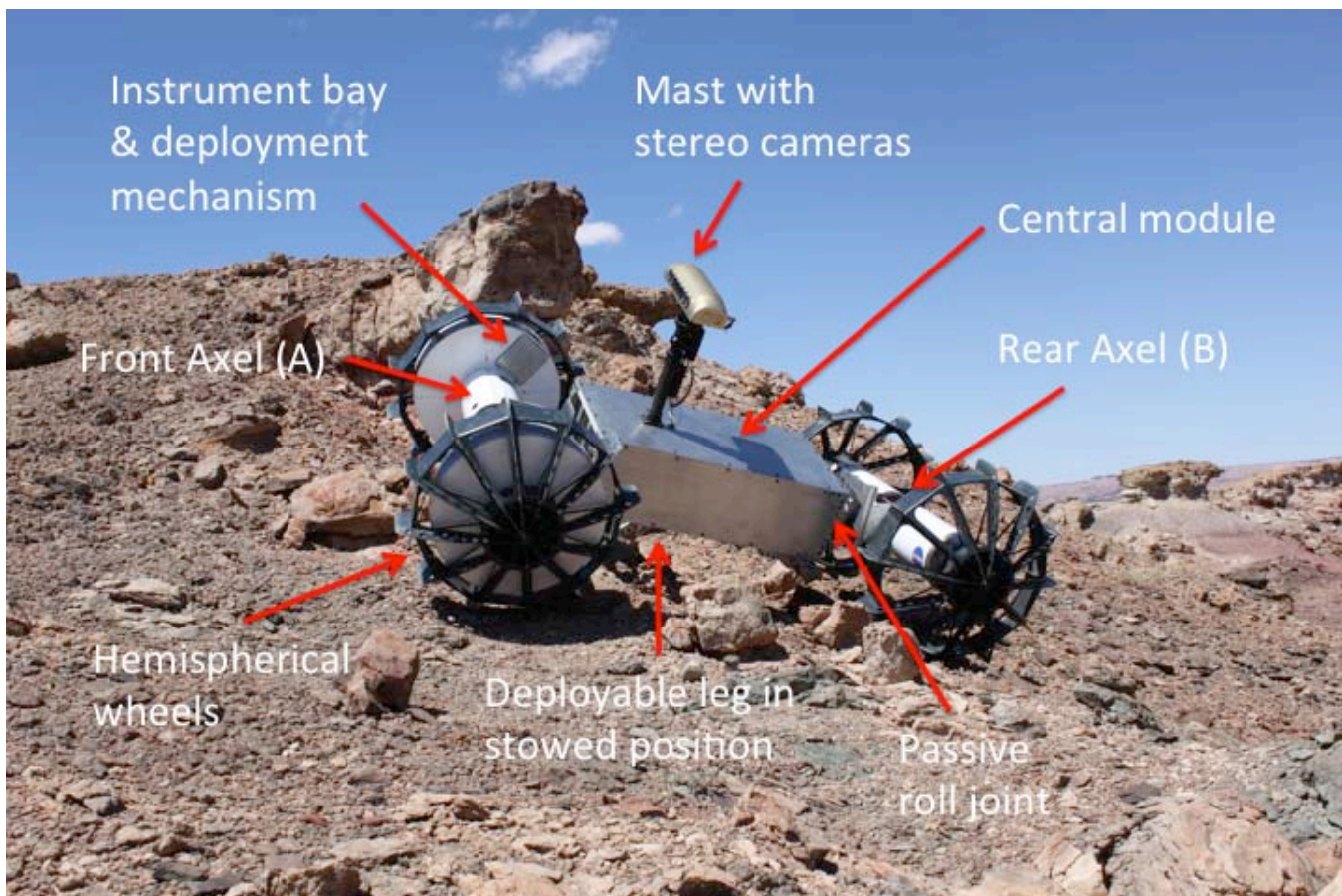


Figure 2 – The DuAxel rover system is comprised of two individual Axel rovers docked to a central module.



Figure 3 – The DuAxel rover drives from the landing site to the edge of severe terrain and then deploys a single Axel into the area of interest.

Extreme Terrain Robots

Several robotic concepts and platforms have been examined for exploring extreme terrains. Both legged and wheeled robots, as well as tethered and untethered robots, have been proposed, several of which were built and fielded. In the 1990s, Carnegie Mellon developed a tethered legged robot to explore active volcanoes. Following a successful descent into the volcano, the robot, named Dante II, tipped to the side during its ascent ending its mission (Bares & Wettergreen, 1999). Another tethered robot is the six legged ATHLETE, which is designed to handle cargo in support of sustained human presence on the moon. The ATHLETE robot traversed slopes greater than 20° with the aid of a tether (Wilcox et al., 2007). The inherent complexity of legged platforms with their large numbers of actuators leads to systems with greater potential for failure (albeit with some added redundancy) and can be challenging for the power/mass constrained environment of space applications.

In addition to these legged robots, a number of wheeled robots with either active or passive suspension mechanisms have been considered. Passive suspension robots, which conform to the terrain, include the six-wheeled rocker bogie planetary rovers: Sojourner, MER, and MSL rovers. Rovers with active suspension mount the wheel on a link that can lift each wheel independently off the ground. Such platforms are often designed to control/lower the center of mass to provide great stability. Examples of such platforms include the JSC Chariot, Nanorover (Wilcox et al., 1997) and the SCARAB rover (Bartlett, Wettergreen, and

Whitaker, 2008). Despite this ability to either conform to the terrain or control center of mass, steeper slopes are likely to require an external force, such as that provided by a tether.

The Cliffbot project (Pirjanian et al., 2002) demonstrated a four-wheeled tethered rover operating a steep sloped while attached by two tethers to two rovers at the top of the cliff. Using two tethers allows the rover to move across the slope, but this advantage diminishes as the rover descends deeper into the crater. The Cliffbot used the rim rovers to feed the tethers, which risks higher abrasion as the tether constantly scrapes the rocks. Moreover, the Cliffbot cannot recover from tip-over, and the problem of planning the motions of two tethers adds extra complexity.

In addition to the six- and four-wheeled rovers, two-wheeled, tail-dragging robots have been investigated, dating as far back as the early 1970s. Among recent developments of these two-wheeled robots are the Scout (Stoeter & Papanikolopoulos, 2006) robots designed for military applications. Another example is the CESAR rover (CESAR Rover, 2011), which was the winner of a mobility challenge organized by the European Space Agency. Such platform share many characteristics with the Axel rover, but have primarily been operated without a tether.

2. Axel Rover System Design

Overview

Each Axel rover is comprised of two wheels, a main body in which the avionics, stereo imagers, batteries and actuators reside, and a caster arm. The hemispherical wheels prevent the rover from being statically stable on its side in the event of a roll over. The wheels are cantilevered over, and provided protection for, two removable instrument bays. The inherently symmetrical design allows for uncompromised mobility in either orientation. The rover weighs 39 kg and can support an additional 10 kg worth of instruments/sampling devices.

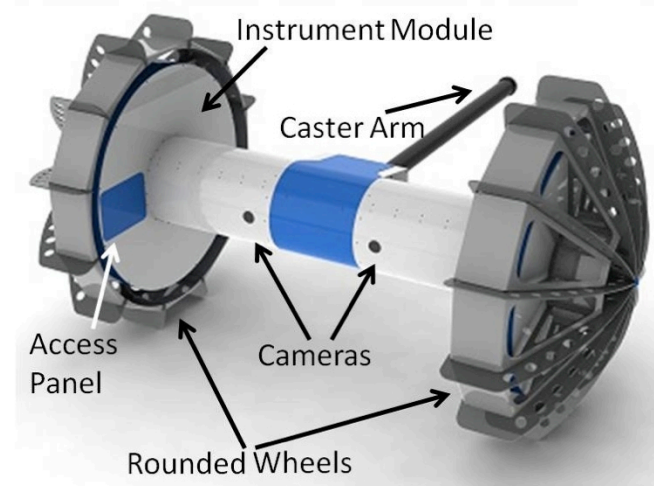


Figure 4 – Rendering of the Axel Rover

The pointing of the instrument bays and cameras with respect to the terrain can be precisely controlled independent of the tether's operation. This represents a significant improvement over former versions of Axel, where the instrument pointing was coupled to the tether reeling, which can be controlled by a single caster arm actuator. While prior Axel versions were able to point instruments when the tether was slack, that ability was compromised when the tether had to be taught (i.e. on steep cliffs where the wheel/wall contact is unstable without a taught tether). Therefore, on steep or vertical walls, orienting the instruments would also result in either raising or lowering of the rover along the wall. This limited the measurement intervals to every $2\pi r$ meters, where r is the

body radius (which, in previous versions is also the spool diameter). In this new version, the tether is wrapped around an actuated drum and fed through the separately actuated caster arm. In order to point the instruments/camera without causing relative motion with the terrain, these two actuators are run in the same direction as each other and opposite to the wheel rotation. Doing so causes the amount of deployed tether to remain unchanged while causing the body to rotate with respect to the terrain. This allows for multiple instruments to be mounted radially in each instrument bay and each be rotated into view of the same target without ascending or descending the slope. Depending on spatial resolution needed for the measurements, either of these two options can be considered for a flight rover design.

Because Axel deploys/retracts its own tether, there is little relative motion with respect to the ground, limiting the opportunities to abrade or snag the tether and allowing for a smaller tether than would otherwise be required. The new Axel tether contains both mechanical strength members and four 28 gauge electrical conductors spun around a nylon core and surrounded by a Vectran strength member and an abrasion resistant layer (see Figure 5). The conductors are used to trickle charge batteries that reside in the rover body as well as communicate with it beyond line of site. An internal slip ring carries data and power across the rotating drum joint. An additional slip ring allows for power and data to cross the rotating joint between the body and the caster arm where an active tether winding mechanism, instruments, or sampling devices may be integrated.

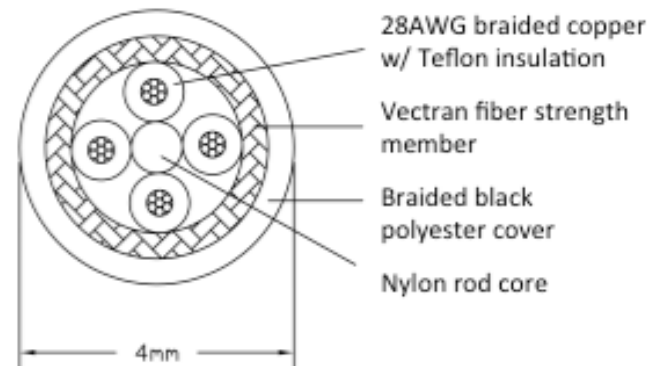


Figure 5 – Cross sectional view of the Axel tether

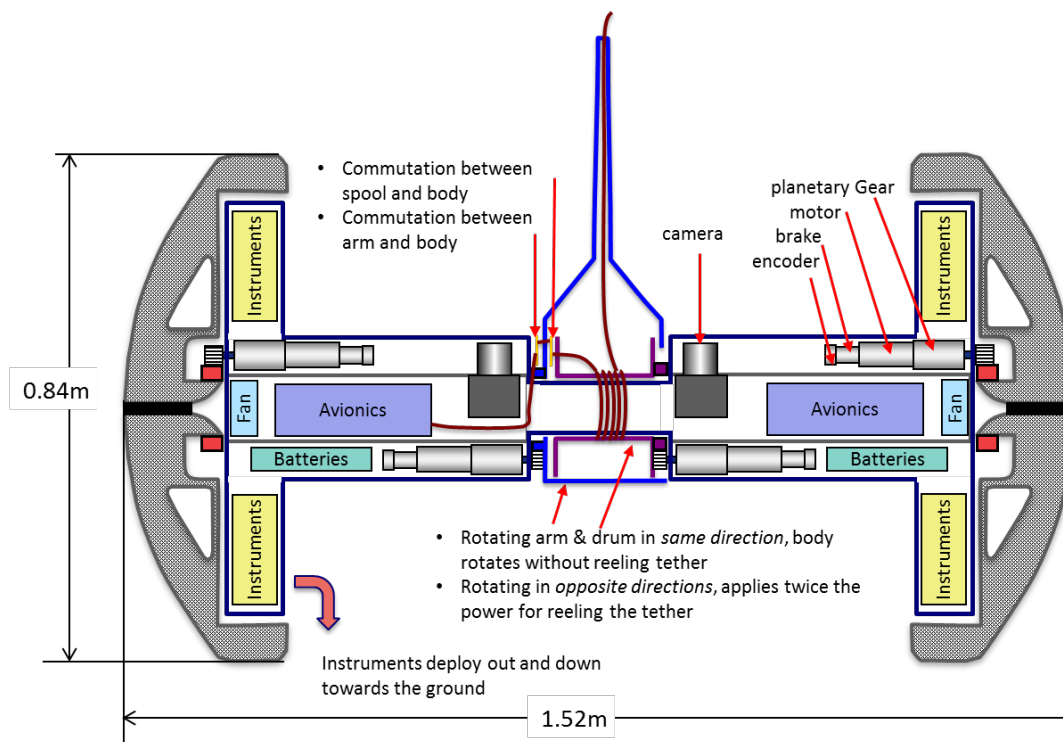


Figure 6 – Schematic representation of the Axel rover system.

Computation & Power

The central body of Axel is comprised of sheet metal ribs riveted together to form a rectangular tube. The main avionics are mounted to flat sheets that fasten to the chassis tube to allow for easy installation and repair. The avionics are comprised of a PC104 stack with an Atom N450 1.67GHz processor, a FireWire board that supports two Pt. Grey Flea 2 cameras, a DC-to-DC conversion board, and a CAN bus interface board. The CAN bus board communicates with Elmo Whistle motor controllers that are distributed throughout the rover in close proximity to their respective actuators. The 1024×768 color cameras are mounted in a stereo configuration with a 27 cm baseline. The main chassis also houses a wireless 802.11 Ethernet module and a Microstrain 3DM-GX3 MEMS IMU. Axel can accommodate four Thunder Power 22V 8Ahr Lithium polymer battery packs and operate for approximately eight hours. The batteries can also be trickle charge via the tether to achieve prolonged operation.

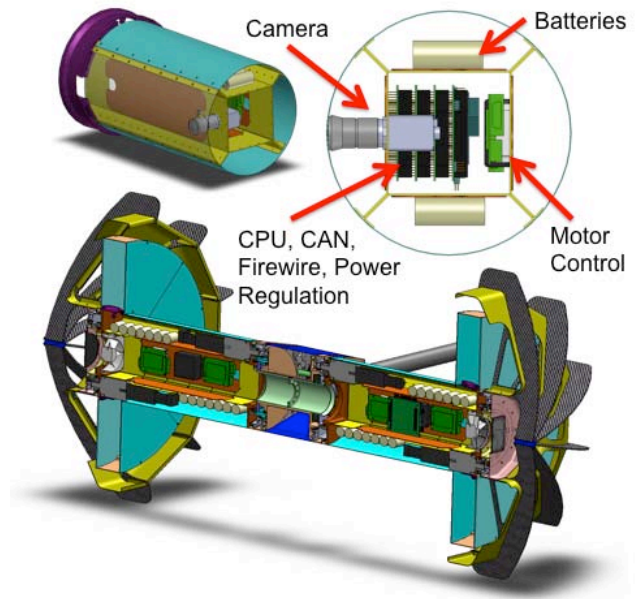


Figure 7 – Cross sectional views of the Axel rover showing the packaging of the avionics.

Primary Actuator Design

The desired instrument payload volume drove the overall rover sizing and initial mass estimation. Consistent with other JPL rovers, the wheel actuators are sized to provide a continuous rim thrust equal to 50% of vehicle weight. From the overall size the desired wheel torque was found to be 120Nm. Additionally, it was desired that the wheels propel

the rover at a 10 cm/s at this max torque value. The tether drum and caster arm actuators were each sized to reel in/out tether at 5 cm/s under maximum torque (64 Nm). By running the tether drum and caster arm actuators in opposite directions, the tether speed and load can match that of the wheels.

Figure 8 shows the common actuator module whose design is used to drive each of the wheels, the caster arm and the drum module, thus reducing the unique part count for the Axel rover. Common commercial off the shelf 24V, 120W brushless DC motors were purchased from Maxon and used in each of these actuator modules. The actuators also each have a planetary gearbox, 500 counts/revolution optical incremental encoder, and a safety brake, which uses power to disengage. Each wheel motor drives a four-stage 353:1 planetary gearbox. The tether drum and caster arm motors drive three-stage 126:1 planetary gearboxes. To allow the motors to be mounted off of the main body axis, a final 6.67:1 spur gear pass is driven by each of the four planetary gearboxes.

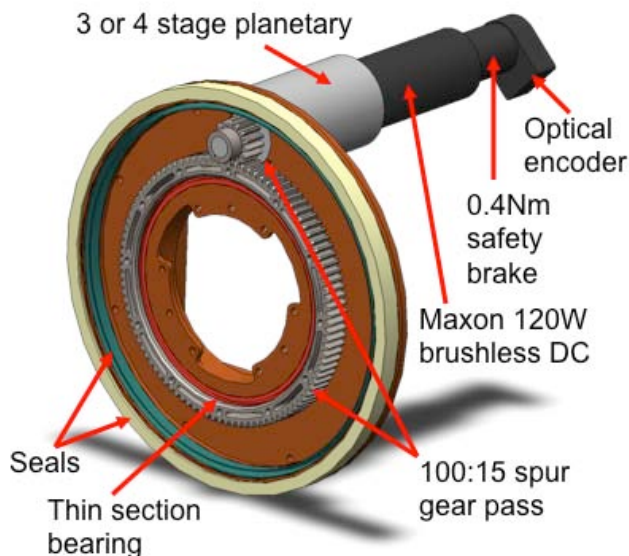


Figure 8 – Common Actuator Module used for Axel’s four primary degrees of freedom.

The spur pass permits the passage of harness and cooling airflow to pass through the center of the rover. The output thin section bearings that support the spur pass are protected from dust intrusion via a three stage sealing strategy derived from the MSL and MER rovers. This system consists of an outermost Nomex felt seal and an inner spring-energized graphite impregnated Teflon seal separated by a pseudo labyrinth machined into the associated mounting hardware.

The power-to-disengage electromagnetic brake located on the back of input shaft does not draw any power when the actuator is not in use. The brakes will spring closed and prevent the actuators from being backdriven in the event of a power failure during motion. This feature also allows the Axel to remain static on a vertical slope without requiring

additional power.

Instrument Deployment Mechanism

The Axel instruments are deployed from the instrument bay down to the surface by way of a simple four-bar linkage mechanism. The motor controller driving the actuator for this mechanism limits the current such that it will deploy out into contact with the surface, regardless of local topography. The instruments are nominally mounted to the back of a plate that also serves as a protective cover when the instruments are stowed. Each mechanism can deploy instrument heads or devices as large as 12.5 cm × 8.5 cm × 8.25 cm and the instrument bay has additional storage volume for supporting electronics. Alternative mechanisms can be used for deploying large instrument heads or devices. Sample acquisition tools, such as a small drill or scoop may also be deployed to the ground from this mechanism.



Figure 9 – The Axel UV reflectance spectrometer and microscopic imager being deployed to the surface.

The current version of Axel hosts a USB2000 reflectance spectrometer and a DinoLite AM311S digital microscopic imager on one deployment mechanism. The two instruments are focused at 5 cm below the bottom of the sensor heads. A thermal contact probe is mounted on a separate deployment mechanism, which extends the contact probe beyond the mounting plate using a small mechanism attached to the deployment mechanism. There are an additional six bays on each Axel available for hosting instruments and their supporting electronics. As the above

image shows, Axel can stop on a slope and rotate its body to expose the various instruments to the same science target without ascending or descending the slope. This ability to rotate the body with respect to the terrain can also be used for collecting samples. A scoop can be attached to the instrument bay door, and rotating Axel's body will sweep the scoop into contact with the surface and up again.



Figure 10 – Axel deploying instruments on a slope.

Tether Tension Measurement

Twelve radial springs are distributed between the output of the tether drum actuator and the tether drum itself. This arrangement forms a mechanism similar to a spring plate in an automotive clutch and has several uses. Firstly, in the event that Axel experiences a sudden drop (perhaps when sloped terrain collapses locally) the springs will act to soften the shock load on the rover and tether system. In addition, the spring deflection is used as a means of estimating tether tension. This is achieved by monitoring the windup between the tether drum and actuator output via a high-resolution absolute encoder. This windup is linearly proportional to the torque on the tether drum. By estimating the amount of tether presently on the drum and hence its radius, the tether tension can be computed. Future work will incorporate a tension direction sensor to complement the aforementioned tension magnitude sensor.

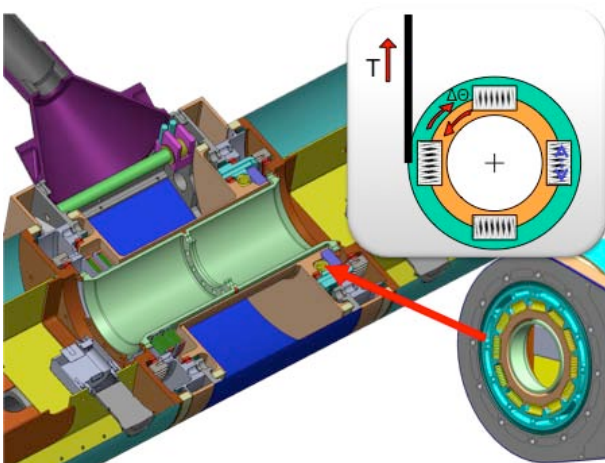


Figure 11 – Axel tether tension sensing system.

3. Field Testing

The new Axel and DuAxel rovers were recently tested in natural and manufactured sloped terrain at two field sites. The first test took place at a road aggregate quarry in Canyon Country, California in March 2011. Slopes traversed ranged from 65° to nearly vertical. Two remotely tele-operated runs up and down a 20 m cliff were successfully attempted. Each of these runs was preceded by the DuAxel system driving on the relatively flat terrain leading up to the cliff's edge, passively deploying the anchor leg, and undocking the Axel. A successful re-docking of the Axel and passive retraction of the anchor leg followed each ascent. This test was the first end-to-end demonstration of the Axel/DuAxel notional surface operations architecture.



Figure 12 – Axel descending a nearly vertical slope at the Vulcan quarry test site.

The second round of field testing occurred in June 2011 near the Black Point Lava Flow, approximately 100 km northeast of Flagstaff, Arizona. The field site is considered to be an excellent Mars analog and was jointly used for tests in support of the Mars Science Laboratory rover. Prior to this test, a passive roll joint was added to the DuAxel chassis that allowed each of the two Axels to rotate with respect to each other and aid in traversing obstacles. In this configuration, the DuAxel was driven hundreds of meters on slopes reaching up to 35°.

Axel was subsequently deployed on slopes ranging from 30° to 80°. Some of these slopes included sharp vertical transitions from flat terrain. One slope was littered with boulders with diameters that exceeded the wheel diameter. In each case, Axel successfully navigated the terrain, albeit with careful path planning and adaptation from the operator. These tests highlighted both the need for and challenge presented to eventual onboard autonomy algorithms.

This field trial saw the first use of the science instruments on natural slopes. The principle of pointing multiple instruments to the same target without advancing up or down the slope was successfully validated. A technique in which one wheel was rotated while the other degrees of freedom remained fixed was used to locally scuff the terrain and provide freshly exposed soil to the instruments was also demonstrated.

These tests also included a load cell that was connected in-line with the tether for the precise measurement of tether tension. Forces up to 750N were recorded, which maintains a 5x factor of safety under the 4,450N limit of the tether.



Figure 13 – Axel descending a boulder ridden slope in Arizona.

4. Conclusions & Future Work

The Axel and DuAxel rovers provide a viable means for accessing otherwise insurmountable terrain. The team has successfully demonstrated the ability of the DuAxel system to deliver two Axel rovers from a safe landing zone to an area of extreme terrain, without consuming valuable tether length. In addition, Axel has proven to be an effective and robust means of carrying and deploying numerous surface science instruments and sampling mechanisms precisely on challenging slopes.

In the testing that has taken place to date, the operator has been afforded a bird's-eye-view of the slope. Future work will include the addition of onboard autonomy to enable operations only relying on the imagery provided by the on-board stereo cameras. The development of docking elements that allow DuAxel to achieve improved terrain conformance and/or Ackerman-like steering will also be undertaken. An early concept of this work is shown in the following figure in which the two Axels are permitted to roll with respect to each other and a differential places the central module at the mean angle between the two (similar to the suspension system used on MSL).

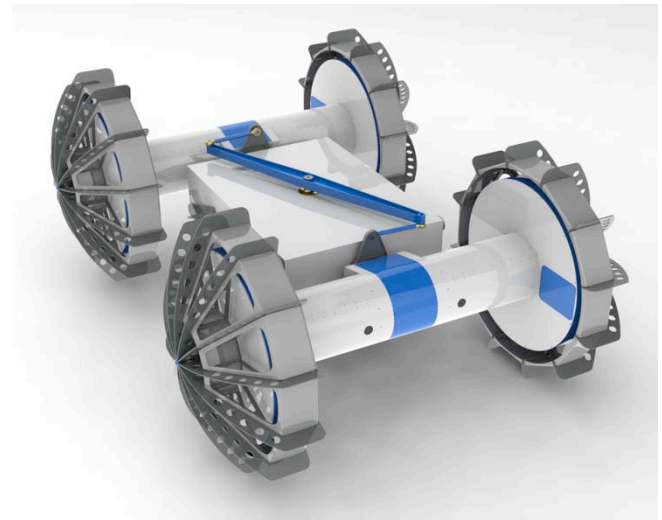


Figure 14 – DuAxel differential roll suspension concept.

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Biographies



Jaret Matthews is a senior engineer in JPL's Mobility & Robotics Section, which he joined in 2003. He was responsible for the mechanical design, fabrication, assembly, and testing of the new Axel rover. He is presently serving as a mobility systems engineer for the Mars Science Laboratory rover that will be launched in November. He recently served as principal investigator for the JPL/Michelin Lunar Wheel and as manager/lead engineer for the ATHLETE lunar rover project. Jaret received the 2011 NASA Exceptional Achievement Medal for his work on ATHLETE. He holds a BS in Aeronautics and Astronautics from Purdue University and a MS from the International Space University. His primary interests are in the design and testing of planetary mobility system concepts.



Issa A. Nesnas is a group supervisor in the Mobility and Robotics Systems section at JPL and the principal investigator of the Axel/DuAxel extreme terrain robots. He has over 20 years of experience in robotic systems design and autonomy software. He was also principal investigator on the multi-institutional reusable robotic software (CLARAty). He has contributed to the development of the Mars Science Laboratory project both to the entry, descent

and landing and to the motion control for rover mobility. Prior to joining JPL in 1997, he worked at Adept Technology, Inc. developing technologies for high-speed vision-based robotic applications. Issa received a B.E. degree in Electrical Engineering from Manhattan College, NY, in 1991, and earned the M.S. and Ph.D. degrees in robotics from the Mechanical Engineering Department at the University of Notre Dame, IN, in 1993 and 1995 respectively.