Technologies toward Lunar Crater Exploration

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Abstract

The primary challenge of descending steep, loose slopes is avoiding avalanche, tipover and maintaining control of locomotion. Theory suggests that for loose, granular soil,the strength lies under, not on, the surface. This has not hitherto been exploited for controlling robot descent. In order to take advantage of this, a prototype robot capable of utilizing sub-surface strength was developed and tested. Two unique features are low center-of gravity and an actuated plow capable of penetrating the ground for controlling descent and facilitating pivot. Tests show unprecedented control during descent on loose soil slopes up to 40°. Avalanche sliding is reduced twenty-fold , pivot turning is improved threefold.

1 Introduction

Controlled descent of crater slopes is a keystone to exploring lunar craters. Models for lunar craters estimate loose regolith slopes at 30 - 40° inclines. In order to explore rover technologies for this regime of locomotion, a prototype rover is presented. The primary objective of this prototype is to explore and develop concepts of locomotion for crater descent. Research focuses on technologies and configuration requirements for planetary rovers intended to descend into craters. The primary innovation is the use of plowing to control descent.

1.1 Robotic Configuration for Exploration

This report describes a configuration with actuated plowing, low center-of-gravity, high flotation, forceful traction, and mobility control. Steep crater descent drives the requirements of rover design, pushing considerations of physical configuration and technology.

Capability	Configuration
Stability	Low center-of-gravity
Forceful Traction	Tracks
Handling loose soil	High floatation
Descent and turn	Plowing

Most planetary robots are unsuitable for maneuvering on crater walls. They are top-heavy due to ambitions for ground clearance and for placing photovoltaics,

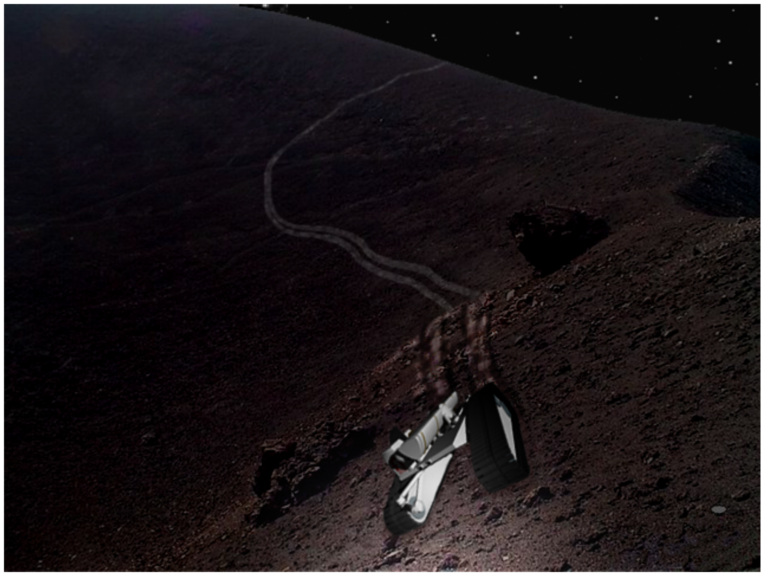


Figure 1: Concept image of a tracked Icebreaker rover ascending the exterior slope of a lunar crater. The stable rover might serpentine up the slope rather than ascend directly. Its drill is carried low and horizontal until needed.

masts, and science payload up high. A visual concept of a low, stable crater-ascender is illustrated in Figure 1.

1.2 Objectives and Significance

This study targets mobility in craters, specifically controlled descent of unconsolidated angle-of-repose material. Motivations include polar resource missions and investigations illuminate technical robotics issues for evaluating resource presence and extraction, routes of access, and other factors important to broader exploration. Table 1 identifies four specific objectives and their significance.

Surface operations consist of entry into and activities within permanently dark regions. Such sorties are essential for characterizing ice. By nature of their location in deep depressions, cold traps will also limit line-of-sight communications with Earth.

Objective	Significance
Measure performance of low-mass tracked locomotion on slopes	Establish capability for crater ascent/descent. Identify issues with tracked locomotion
Prototype and test a plow for braking and control of turning on slopes	Establish feasibility of controlled slope descent and obstacle avoidance
Study power for loose material locomotion	Bound power requirements for lunar rover
Study integrated rover and payload	Define concept for lunar crater rover

Table 1: Objectives and significance of the Lunar Rover Initiative

Figure 2: Prototype Icebreaker descending a 35° slope

2 Testing and Physical Results

The Icebreaker prototype was primarily constructed to analyze the use of plowing to control descent and tracked locomotion in a low-slung frame. Testing revealed remarkable maneuverability on extremely steep terrain and limitations of the vehicle. Particular emphasis was placed on track and side-slope slipping, because they heavily impact control algorithms and must be modeled to enable autonomous driving.

Figure 3: Tracks during descent of a 35° slope show a relatively straight trajectory.

2.1 Plow Testing

Notable descent and turning control was achieved with the plow. Tests measured the amount of slip during descent and turning, with data collected at varying plow depths. Slip was measured by comparing survey measurements and an ideal dead reckoning estimate of traversal generated through on-board vehicle sensing.

2.1.1 Turning with Plow

The primary benefit to plowing is the improvement in control authority. Early qualitative testing showed that control authority in steep descent without a plow resulted in poor control authority - the rover would break loose from the surface, sliding uncontrollably.

In-place turning was tested with 0m, 0.07m, and 0.2m plow depths. The rover started facing perpendicular to the line of steepest descent, turning to face downhill, and then side-slope the opposite direction, sweeping out a 180° arc. Figure

4 shows the initial orientation of the rover for clarity. Figure 5 shows total accumulated slip as a function of yaw relative to the path of steepest descent. Least-squares fit of cubic polynomials are also shown, which were produced during attempts to analyze the data. In addition, Figure 6 shows slip-rate as a function of yaw. Moving from no plow deployment to 8" deployment reduces total slip by a factor of 3.

Figure 4: Rover positioned at the start of a turning test, with no plow engaged.

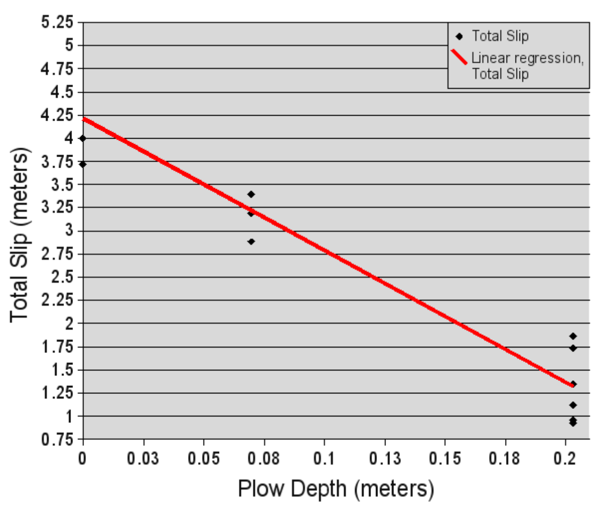


Figure 5: Total slip during in-place turning with various plow deployments

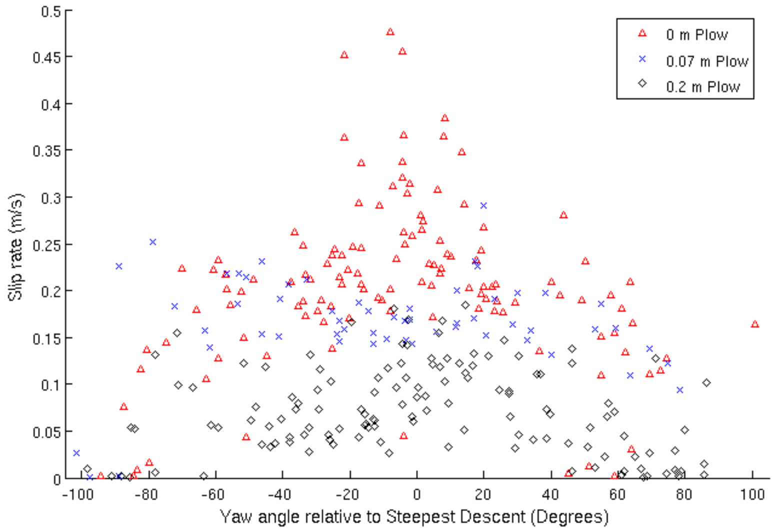


Figure 6: Slip rate vs. yaw angle during in-place turn maneuver.

2.1.2 Descent with Plow

For straight descent, control authority focused on the ability to descend at a commanded velocity. With descent being along the maximum gradient, slip works to overshoot commanded velocity. Testing is relatively straightforward in this scenario - point the rover along the line of steepest descent, engage the plow to the desired depth, and drive the rover for 10 meters along the slope. Slip can then be measured by comparing the total traversal distance measurement from dead reckoning and the Total Station. At least three trials were performed with the plow set to 0m, 0.07m, 0.14m, and 0.2m, with the results shown in Figure 7. The data from this graph shows two main results from the data. The first is that the slip rate decreases approximately 20 times between no plow and a 0.2m plow depth. Second, the slip rate turns out to relate linearly to plow depth.

2.2 Non-Plow Ascent/Descent Slip Test

The prototype has ascended, descended, and traversed lunar relevant slopes without plow and descended with plow. A testing area at a 15° angle of dry, fairly loose dirt with average particle size of about half a centimeter was prepared. The test procedure consisted of noting both track positions, driving the rover forward

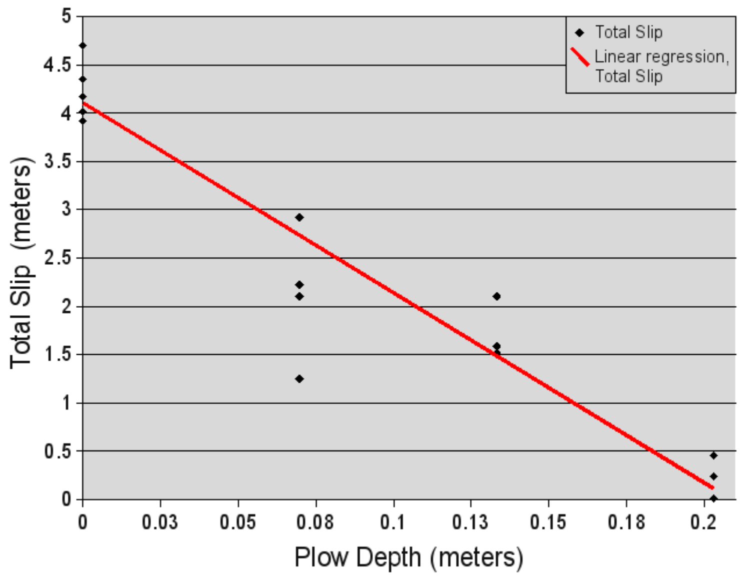


Figure 7: Slip rates during linear descent with various plow depths.

Trial Type	Trial #	Left Track Distance Traveled (cm)	Right Track Distance Traveled (cm)	Left Track Slip	Differential Slip
Ascent	1	304.80	307.7	0.00%	0.95%
Ascent	2	304.80	304.8	0.00%	0.00%
Ascent	3	299.72	289.6	1.67%	3.37%
Ascent	4	303.53	302.3	0.43%	0.40%
Descent	1	312.42	314.3	2.49%	0.61%
Descent	2	313.69	313.7	2.92%	0.00%
Descent	3	318.77	326.4	4.59%	2.38%
Descent	4	316.23	317.5	3.74%	0.41%

Table 2: Data for 15° ascent and descent.

for one whole revolution of the left track, and then noting the difference in position of the right track. Additionally, total distance traveled was noted. This procedure characterized track slipping for both ascent and descent, and representative data appears in Table 2.

Figure 8: Icebreaker descending a 35° slope.

2.3 Non-Plow Sideslip Test

Sideslip is the tendency for a vehicle to displace laterally while attempting to move forward across the fall line of a slope. It is important that a design minimizes sideslip to allow accurate control and obstacle avoidance.

When the prototype traverses sideways across 35° slopes composed of loose particulate, significant downhill side-slipping occurs. To maintain a given altitude during sideways traverse the rover must constantly be reoriented toward the top of the hill.

The sideslip testing procedure was to drive the vehicle forward for one full rotation of the left track directly perpendicular to the angle of steepest descent and measure the resulting lateral displacement down the slope. Data for this test on the 15° slope is displayed in Table 3.

2.4 Non-Plow Quality of Control on Steep Slopes

Control authority is the ability of a vehicle to drive an arbitrary path. It can be limited on steep slopes by traction, actuator torque, and orientation. The Icebreaker prototype is not limited by torque or longitudinal soil traction and will

Figure 9: The prototype rover is traversing mounds of loose slag material, showing significant sideslip.

Trial #	Left Track Distance Traveled (cm)	Slip Distance (cm)	Slip per meter
1	308.61	10.160	3.29 cm
2	309.88	11.430	3.69 cm
3	309.88	3.810	1.23 cm
4	309.88	7.620	2.46 cm

Table 3: Sideslip for 15° traverse.

steadily climb the line of steepest ascent/descent on slopes at an angle-of-repose of 35°. It can ascend these slopes at its maximum speed of 7 cm/sec. During descent uncontrolled slipping occurs at maximum speed, but is less likely at 2 cm/sec. Slow acceleration also helps control slipping.

Control authority is limited on these steep slopes, however, because the rover is unable to turn in place regardless of initial orientation. As the track rotates it dislodges the surface soil causing a landslide that carries the rover downhill for as long as the tracks are turning. Leaving one track fixed is slightly more productive because of the anchoring effect, but remains insufficient for arbitrary control. Some slippage still occurs regardless of what turning method is used.

Control authority is also limited in areas of sudden changes in slope angle. The prototype rover's fixed frame does not allow for full ground compliance, which causes reduced contact area. This increases ground pressure, decreases traction, and introduces dynamic effects to the rover's motion, all of which hamper control authority. An improvement in ground compliance may be realized by introducing a degree of freedom between the two tracks, allowing tracks to rotate relative to each other to maximize contact with the ground. Improvements along this vein are being pursued in continued research on locomotion.

2.5 CG Location

The center of gravity is 0.6 cm below the axle or 13.2 cm from ground. The x-y location of the center of gravity is 68.9 cm from the front of the rover and 56.8 cm from the right edge, or within 2 cm of the spatial centroid of the body.

A low CG provides more even distribution of ground pressure due to a shorter moment arm between the ground and the vehicle mass. Traction and even, low ground pressure are vital to navigating steep terrain. Components must also be balanced between the two tracks to provide mass symmetry. The actual center of gravity position along the x-y plane of the chassis was found by balancing the robot on a vertical, narrow post. A method based on measuring weight at the axle for different inclinations provided the z-height of the CG.

2.6 Testing Site Soil Samples

In order to test technologies for descending into lunar craters, testing sites capable of providing relevant conditions must be used for data collection. In order to do this, soil samples were taken from the proposed testing site, a local slag heap, and analyzed for similarity to lunar soil.

The study of the physical and mechanical properties of lunar soil serves as the basis for designing unmanned lunar spacecraft [10]. Some key properties include moisture content, specific gravity, friction angles, shear strength, and particle size.

On the moon there is no surface moisture. During our testing the average moisture 0.076m below the surface was 4.95%. At a depth of 0.152m the soil moisture content rose to 21.3%.

Specific gravity is the density relative to water. The regolith that Icebreaker was tested on had a specific gravity of 2.92 determined using water pycnometry. Lunar samples had specific gravities ranging from 2.31 (sample 12002,85 from

Apollo 12) to 3.51 (sample 70017,77 from Apollo 17) also using water pycnometry. Friction angle also play a key role in traversability for a lunar rover. Lunar friction angles are based from two different models. The Surveyor model has a best estimate of 35-37 degrees. While the Apollo model has a best estimate of 30-50 degrees. Icebreaker's testing regolith had a friction angle of 52.6 degrees. See Figure 10 for soil size comparison [11].

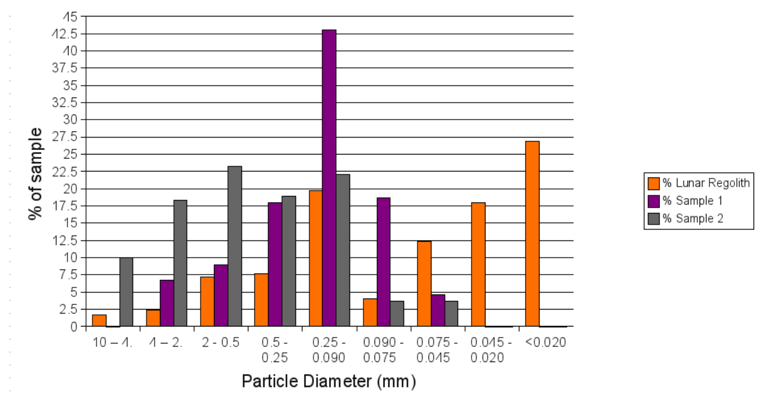


Figure 10: Comparison of particle diameters between Lunar soil samples, and local testing site samples.

3 Design and Configuration

3.1 Formulation

For climbing, low center of gravity prevents tipping on steep slopes, high flotation maximizes locomotion in loose soil, and low ground pressure limits the rover sinkage. Tracked vehicles exhibit advantages for these characteristics.

Tracked vehicle stance can be wide, long, and low for stability in steep terrain, providing a compact rover for tight integration into a lander and easy deployment. To keep center of gravity is kept low. Components like batteries and computers can be placed within the tracks. Tracks can grip terrain and bridge irregularities with high flotation. Increased surface area along the tracks spreads weight to keep ground pressure low. As a result, the Icebreaker rover is capable of the steep ascent and descent of highland terrain and features a low center of gravity, high traction, and low ground pressure.

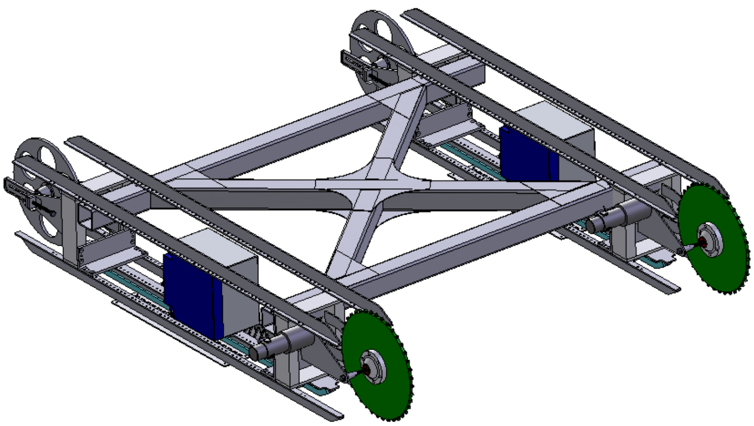


Figure 11: The rover prototype with the tracks removed. Rover components are housed in the side frames. Guide bars take the place of idler wheels, thus providing the necessary room.

3.1.1 Prototype Principles

The prototype aims to remain lunar relevant with respect to mass, volume, and power budgets, but does not address thermal or radiation issues. The decision to focus on mass and power derives from the necessity to answer basic questions about locomotion and refine low-level design decisions before reinforcing to withstand cryogenic cold and radiation.

Since this prototype does not simulate all aspects of a final configuration, like sensing, science, and communications, it is lighter and uses less power than corresponding flight model.

	Mass (kg)	Average Power (W)	Max Power (W)
Flight Model	79	85	235
Prototype	58	36	110

Table 4: Overall System Characteristics of Flight Model vs. Prototype

3.2 Mechatronics

3.2.1 Track Materials

Track materials determine traction and space-relevance, and have little space heritage. Most Earth-based tracks are either elastomer or metal links, neither of which is well suited to space environments. Research into possible track materials and designs begins to determine several possible scenarios for space-relevant tracks.

Fabric based tracks hold the prospect to be light and flexible, and can be prototyped inexpensively. Using fabrics such as Kevlar or Vectran provides the tensile strength and thermal performance necessary for lunar operations, but concerns over abrasion due to lunar dust and torsional rigidity have yet to be tested. Hard links provide opportunities for stronger grousers to grip soil and improve traction, but require careful research and design to ensure that thermal issues do not render tracks inoperable in cryogenic cold. Embedding rigid materials in fabric tracks may deliver flexibility as well as grip strength. Other possibilities include ceramic links to provide high strength without the concerns of cold-welding.

3.2.2 Plow

Loose, angle-of-repose material, physical disturbances of the regolith can result in avalanche type failure modes, resulting in fluid-like flows which can send a rover into uncontrolled slip. Even when direct descent is possible, the additional forces required for turning cause excessive slipping, making obstacle avoidance and spiral descent impossible. A successful rover must develop a way of controlling steep descent.

The strength of granular soil is under, not on, the surface. Digging down with a plow beneath a rover improves descent and turning. The increased soil friction can mitigate slipping caused by fluid-like flows of soil particles near the angle of repose. A plow can reach below the loose surface layer until it reaches more stable and compact soil acting as an anchor against landslides during locomotion.

A plow drastically impacts descending locomotion. This is a result of attempting to turn around a center of rotation which is not centered on the plow, which causes the plow to exert a frictional torque that resists turning.

A plow counteracts any turn which is not centered upon the plow. A rover rotates around the plow until it comes to rest at point furthest down the slope, at which point the rover can no longer move. With a plow in the center of the vehicle, a rover is capable of point turning and driving straight.

Figure 12: Initial plow experiment dragging a threaded rod to set various depths of penetration.

Subsurface features such as rocks or pockets of compacted soil can catch a plow, anchoring the rover to a location with no method of recovery. Changes in the local slope angle or the depth to which the rover sinks into the slope results in the rover catching on subsurface features, leaving the system fragile to minor variations in slope features. Hence the value of a plow actuated for depth control.

Design considerations minimize additional weight, keep the center of gravity low, and provide enough power to drive the plow into the soil. A rack and pinion deploys a pipe - shaped plow to be inserted up to twelve inches into the ground, and withdrawn until the plow no longer engages the ground (Figure 13).

Actuation overcomes the limitations of a static plow system, without impacting the benefits of the plow mechanism. The resulting system is robust to variations in slope angle, sub-surface features, and allows for testing of variation in plow depth on slip experienced during slope descent. Results from testing with the actuated plow appear in Section 2.1.

3.2.3 Chassis

The chassis provides a rigid frame to which tracked side-frames are attached. It provides the majority of the width for the rover, minimizing weight added to the

Figure 13: Icebreaker rover with actuated plow engaged.

vehicle while still providing a rigid frame. A rigid frame maintains the simplicity of design, reducing the complications arising from an articulated or actuated frame.

The side-frames provide an internal volume that contains the components for operating the robot. Instead of idler wheels along the length of the track, Teflon guide bars provide low-friction support without using significant volume. The physical dimensions of the rover determine the stability of stance, and ease of turning. The rover is 1.4 meter long, 1.1 meters wide, and 0.3 meters tall.

3.2.4 Electronics

To simulate radioisotope power supply, a tether provides trickled primary power. Batteries are sealed lead-acid batteries and were chosen to approximate the mass of space-relevant batteries. Using this configuration, the prototype carries 312 Wh of battery power and is capable of running for several hours without recharging.

3.3 Operating in Darkness

Operations in dark environments present challenges unanswered by current planetary rovers. Planetary rovers hibernate through darkness and operate in light, while ice exists in regions of deep darkness. The lack of sunlight and atmosphere mean cryogenic cold temperatures and inapplicability of traditional sensing methods. Issues such as thermal management, configuration, energetics, and perception need to be addressed before pursuing lunar ice. A critical element of surface rover design for the moon is the choice of terrain sensing modality. Sensing terrain in three dimensions enables rovers to autonomously discriminate between hazards and safe pathways. However, sensors traditionally employed for planetary rovers may not be sufficient for autonomous or semi-autonomous operations in the dark on the moon. Stereo vision has been the mainstay for rover terrain sensing but may not be viable, even with active lighting, in the areas of shadow that are actively sought in some science scenarios. LIDAR and line striping, however, are two technologies ideally suited to dark lunar operation. To solve the problem of perception, this research investigated line-striping and LIDAR. A cylindrical lens projects a line of light, which is perceived by a camera mounted 10 to 20 cm away. A triangulation method similar to stereovision, but with much less processing requirement, produces a map of distances to objects. Line striping is ideally suited to darkness and has space heritage on Sojourner [15].

LIDAR, or LASER RADAR, emits a single point of light and measures distance using time-of-flight. By sweeping this beam, it can produce a full 3D map of the world. LIDAR promises to extend the range of accurate sensing to several kilometers [2], providing information on topography and the long-range planning required to successfully descend a crater slope.

Thermal issues from darkness are mitigated by internal heat sources like the radioisotope electrical generator and waste heat from electronics. These provide vital warmth which is distributed to critical components packed closely to minimize heat transfer and associated losses. Energetics need to account for heat generation and utilize power efficiently. These challenges have not been addressed before to allow rover operations in darkness, which requires new approaches and careful research. Current research is developing mechanical configuration with lesser consideration (like monolithic chassis) for thermal management.

3.4 Operating During Communication Outages

Line of sight communications are not reliable at the lunar pole because Earth is low on the horizon at best, and obscured by craters and mountains at worst. Orbiting satellites can provide relay capability, but do not offer continuous coverage. Mission autonomy is imperative to succeed in these conditions.

Standard operation in good communication involves human oversight and plan-

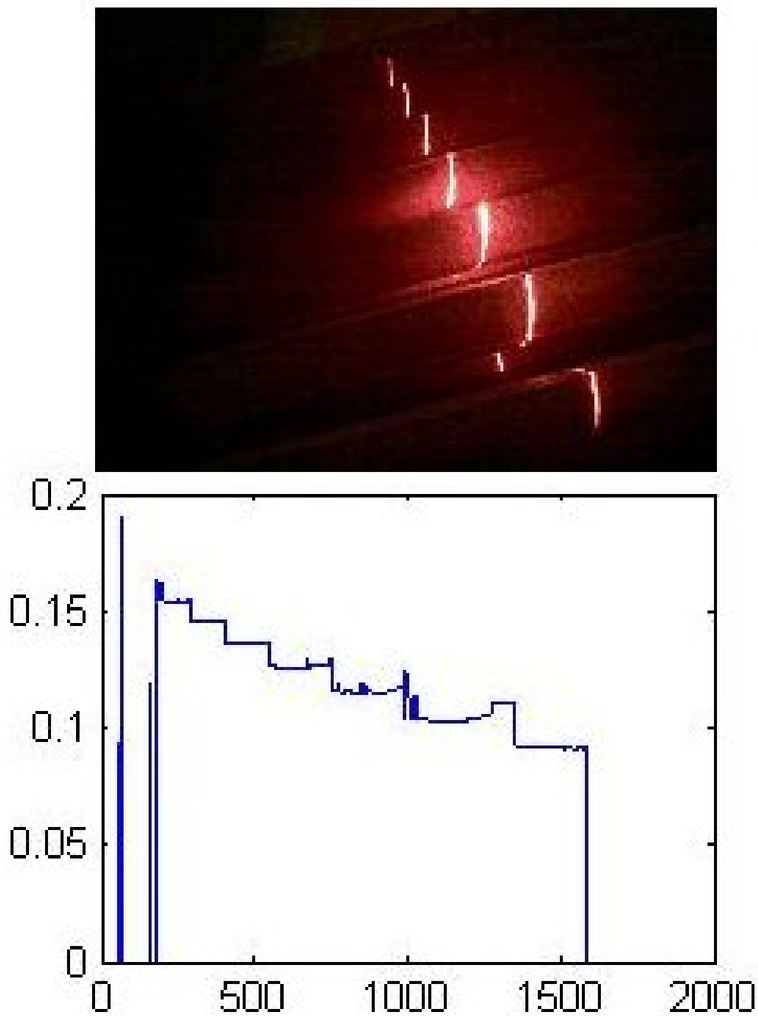
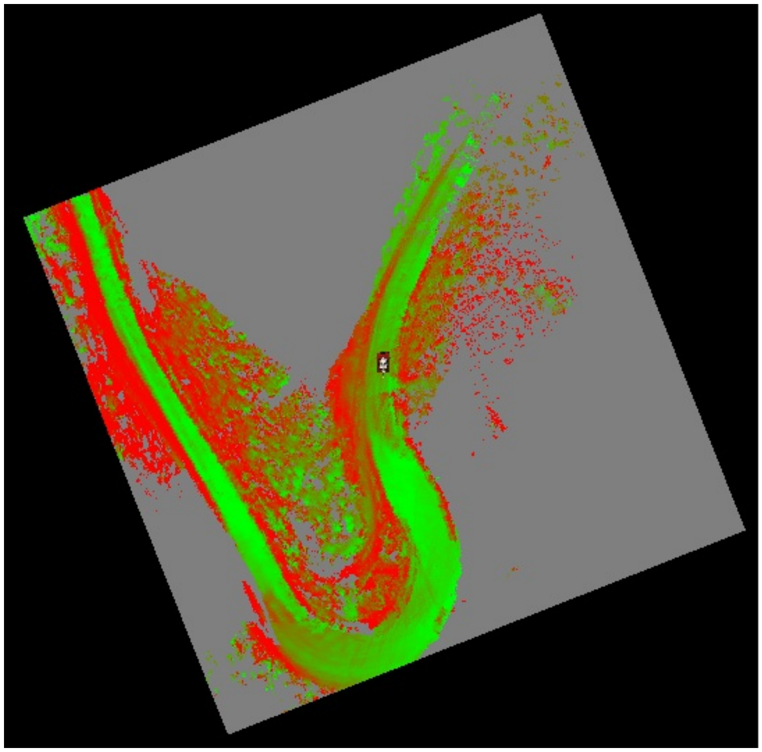


Figure 14: Scene and data collected with prototype light striping device

ning, with autonomy providing a backup. When the link is lost, Icebreaker backtracks and attempts to reestablish. There is no guarantee that the landing site will have communications coverage, so Icebreaker must have contingency to autonomously deploy from the lander and seek a clear signal. On landing antennas are not pointed at Earth so the approach must occur without human guidance.



3.5 Drilling in lunar gravity

Ice on the moon lies below the surface. Finding it requires drilling or trenching up to a meter in depth. Once reached, identifying water conclusively requires manipulation and analysis of a soil sample within range of scientific instruments.

Operating a spinning, thrusting drill applies torque to a rover. Remaining in place despite the low lunar gravity takes rover weight that exceeds drill thrust with margin. Wide stance, good stiffness, and good traction are essential. These are the exact characteristics bestowed by a tracked, low-slung vehicle. Furthermore, the plow system can provide anchoring to resist the drilling torques.

Early work considered using dual-actuation to provide increased reliability and fewer components by using a single actuator to provide power to either the tracks for locomotion or the drill for sampling. The benefits touted were energy efficiency and fewer components. However, additional research determined that the gear box for allowing this separation would result in more complicated parts and vulnerability to wear. Furthermore, power savings can be achieved by separating locomotion and drilling as exclusive, time-sequenced operations.

4 Discussion

In both tests, the data shows a significant improvement in controlled descent with the addition of the plow. These results clearly show the improvement in descent control directly caused by the plow. In the linear testing, the plow provides over and order-of-magnitude reduction in slip, as well as a strong linear correlation between plow depth and slip. For the linear fit, $R^2 = 0.94$, indicating a good fit. For in-place turning, we see a smaller improvement in slip rates overall, with only a factor of 3.2. The results for turning, however, reveal more interesting results when analyzed as a function of slip rate vs. yaw.

Analyzing slip rate, as opposed to total slip, provides insight into slip modes encountered. With no plow engaged, there is a noticeable spike of increased slipping around $0°$, which is not present in the two plots with the plow engaged. This difference matches the qualitative observations which were made during testing - with no plow engaged, the rover would perturb the surface layer enough to break loose in a fluid-like flow, causing the rover to “surf” on top of it. This effect was observed only when no plow was engaged, as shown in Figure 15, and in the data this observation manifests itself as this spike. This result suggests there are two different modes of slipping present: the first mode is riding these fluid-like flows which occur from perturbing the surface layer, while the second occurs from issues of traction on loose soil. The data suggests that the first mode is strongly affected through the use of a plow, with the spike completely disappearing even at 0.02m of plow engagement. This result reinforces the utility of the plow for controlling slip.

Figure 15: Example of fluid-like flows of the soil surface layer forming during a turn execution. Flows are seen as darker soil underneath the tracks of the rover prototype.

5 Conclusions

Tracked locomotion with a low center of gravity can climb and descend loose soil near the angle of repose. Slope descent can be much steeper. Without a plowing technology, control authority on any significant slope is severely limited. The addition of an actuated plow significantly improves control authority descending, driving, and turning. Slip rate is also shown to be linear with respect to plow depth.

5.1 Acknowledgements

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