Rover Configuration for Exploring Lunar Craters

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Abstract

Configuration of locomotion for planetary rovers is motivated by increased interest in exploring lunar polar craters. Current rover designs cannot achieve the ascent or descent required by steep, unconsolidated lunar slopes. New designs must provide locomotive capability for steep climbing, techniques for controlling slip, and safely navigating down and along steep slopes. We propose a locomotion system designed to show unprecedented capabilities in steep terrain through a track-based system featuring a low center of gravity and an actuated, omni-directional plowing device. Experimental results show unprecedented locomotion in steep terrain, capable of controlled ascent on 35° slopes, controlled descent and point turning on 38° slopes. For descent, the use of a plow is shown to reduce slip twenty-fold in linear descent, and threefold in point turns.

Contents

1 Introduction

The discovery of water ice and other important volatiles, such as carbon dioxide and methane, on the lunar surface drives attempts to explore the interior of lunar craters. Lunar polar craters receive little or no direct sunlight, resulting in regions with surface conditions as cold as 40 K [5]. These volatile trapping craters may range in size from a few tens of meters to tens of kilometers in diameter. Viability of extended human presence on the lunar surface will benefit significantly if water is discovered in craters [21]. With evidence that water might exist in cold traps located in craters at the lunar poles [2, 13, 6, 8] controlled ascent/descent of crater slopes is a keystone to exploring these resources.

Models for lunar craters estimate unconsolidated regolith slopes with a 30° to 40° angle-of-repose [9, 10]. These slopes exhibit fluid-like flows of soil, resulting in an uncontrolled "surfing" descent. Theory suggests that for loose, granular soil, strength lies under, not on, the surface [25, 28]. A prototype rover, Icebreaker, is presented to explore rover technologies for this regime of locomotion. Research pushes technologies and configuration requirements for planetary rovers intended to navigate steep crater walls.

Figure 1: Icebreaker rover descending a 38° slope.

Crater mobility must achieve ascent, side-slope traversal, and 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 two specific objectives and their significance.

2 Configuration and Design

Icebreaker's design integrates several concepts to enable navigation on steep, unconsolidated slopes. Rover design considerations originate from aspirations of a sec-

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

Table 1: Objectives and significance of the Lunar Rover Initiative.

ondary lunar mission[4], with research efforts supporting proposal assertions. Table 2 provides examples of how mission requirements and rover design considerations interact. The rover, shown in Figure 1, shows the final configuration addressing these issues.

Mission Requirement	Design Constraint
Ascent/Descent of steep crater walls	Forceful, steady locomotion
Side-slope navigation of steep crater walls	Low center of gravity
Safe navigation on unconsolidated slopes	Technology for controlling slip
Low-cost, low-volume payload	Compact & efficient rover design

Table 2: Mission Requirements and impact upon rover design.

Although mission concepts push rover design, some aspects of lunar operation are intentionally unaddressed by this design. Robot configuration must achieve a stable chassis design and slip-resisting techniques. These must be understood and refined before other issues, such as radiation, thermal, vacuum and lighting are overlaid.

2.1 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. For stability in steep terrain, tracked vehicle stance can be wide, long, and low, providing a compact rover for tight integration into a lander and easy deployment. These properties can be achieved by placing components like batteries and computers 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. No flight-rated tracks exist, a challenge for additional research. The low center of gravity, high traction, and low ground pressure of the Icebreaker rover achieve steep ascent and descent.

2.2 Chassis Design

The chassis, shown in Figure 2 provides a rigid frame to which tracked side-frames are attached. It provides the width for the rover, minimizing weight added to the vehicle. A rigid frame maintains the simplicity of design, reducing the complications arising from articulated or actuated frames.

The side-frames provide an internal volume that contains power, control, and communication 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.

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 center of gravity provides more even distribution of ground pressure due to a shorter moment arm between the ground and the vehicle mass. The resulting traction and low, even ground pressure are vital to navigating steep terrain.

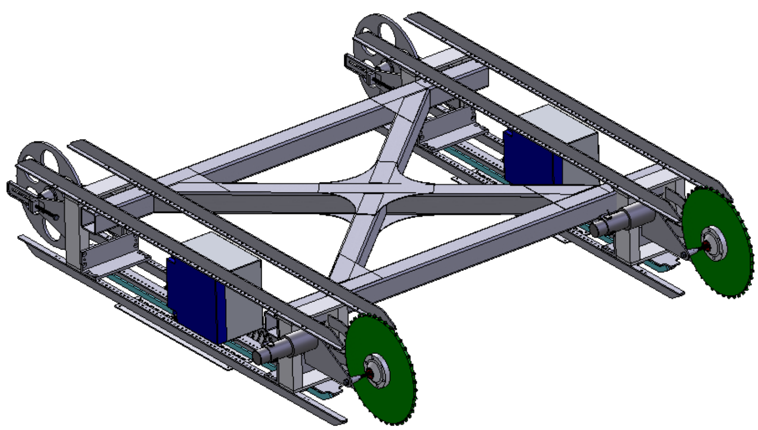


Figure 2: The rover prototype with the tracks removed. Rover components are housed in the side frames. Guide bars take the place of idler wheels, providing volume for components like batteries, computers, and communication.

2.3 Plow Design

In loose, angle-of-repose material, physical disturbances of the regolith can result in fluid-like, avalanching flows which can send a rover into uncontrolled slip. These failure modes are due to shear failures, as predicted by the Mohr-Coulomb Criterion, shown in Equation 1 [25]. The surface layer of granular soil shows low cohesion (c) and normal stress (σ), resulting in low shear strength (τ) on steep terrain [9]. This low surface shear strength results in avalanches, which can cause loss of control during descent. Even when direct descent is possible, the additional shearing created by turning causes surface failures, making intended trajectory, obstacle avoidance and spiral descent impossible. A successful rover must develop a way of controlling steep descent.

$$\tau = c + \sigma * tan(\phi) \tag{1}$$

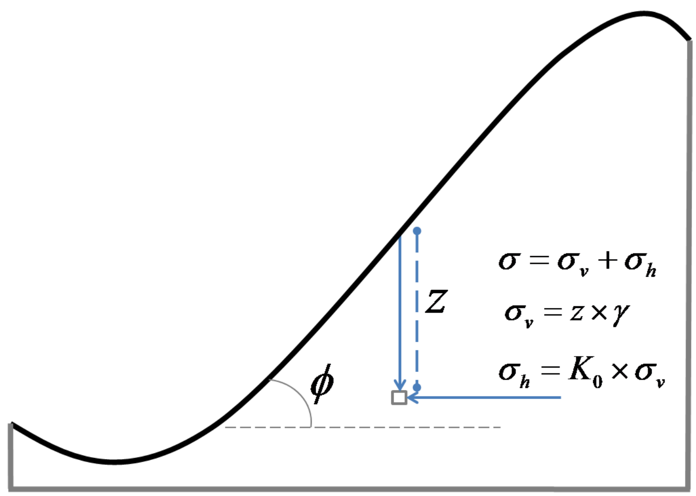


Figure 3: Diagram showing the forces applied to a small unit of soil within an angle-of-repose slope.

The strength of granular soil is under, not on, the surface. Given an idealized, angle-of-repose slope, such as the one shown in Figure 3, the following observations can be made. Assuming the lunar regolith to be uniform in composition, Equation 2 gives the relationship between normal stress (σ) and depth beneath the surface (z). Combining Equations 1 and 2, Equation 3 shows that shear strength increases linearly with depth beneath the surface. Burying part of the rover into the regolith results in greater resistance to down-slope motion and anchoring against avalanches. In order to take advantage of this, an omni-directional plow was developed and installed on the rover. A plow can reach below the loose surface layer to more stable and compact soil, acting as an anchor against slip during descent. The plow consists of a hollow steel pipe 0.15m in diameter tipped with a conical Lexan tip. Since the plow's cross-section is circular, the plow presents omni-directional resistance to slip. Use of the plow does not depend on the orientation of the rover relative to the slope, and surface irregularities do not negatively impact the efficacy of the plow.

$$\sigma = z * \gamma \tag{2}$$

$$\tau = c + z * \gamma * tan(\phi) \tag{3}$$

Early qualitative testing found that inserting a plow into the soil counteracts any turning motion not centered upon the plow. Installing the plow at the rover's x-y center of gravity enables the rover to execute straight lines and point-turns, minimizing any negative impact the plow would otherwise have upon intended motion. The plow uses a rack and pinion mechanism for a compact and lightweight implementation installed low close to the rover chassis. The plow, as seen in Figure 4, can penetrate 0.23 m below soil surface for slip resistance. Testing revealed remarkable maneuverability on steep, loose terrain.

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 actuating and controlling for depth of the plow.

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 0.30 m into the ground, and withdrawn until the plow no longer engages the ground, as seen in 4b.

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 enables testing slip reduction from various plow depths during descent.

3 Experiment Design

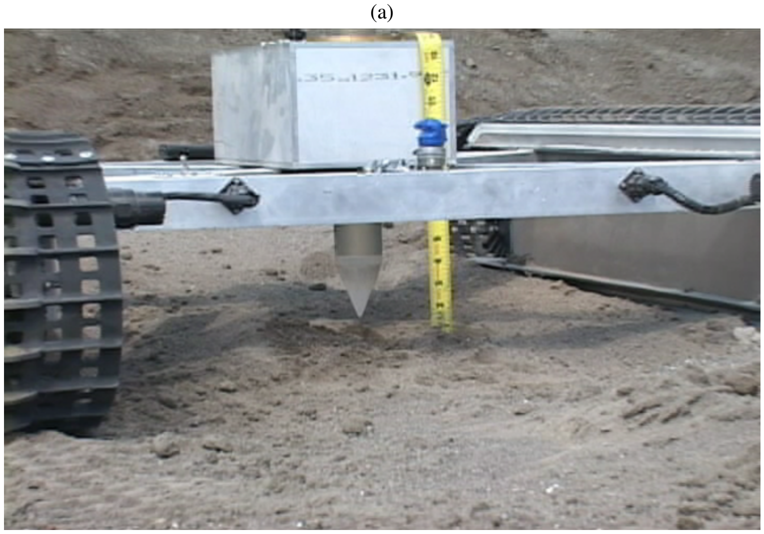
Icebreaker's testing provides empirical evidence to support the systemic validity of a low, tracked configuration with controlled plow resistance. Testing evaluates the impact plowing has on control authority while descending, and provides indications as to future development of the plowing concept. For ascent, testing highlights the capabilities of a tracked, low-slung frame with forceful locomotion. Testing revealed remarkable maneuverability on extremely steep terrain on the one hand and limitations of the vehicle on the other.

Plow testing explores slip in two classes of motion: linear descent and point turns. In both cases steep, unconsolidated terrain confounds the rover's motion. Testing was performed by having the rover drive a single action, and recording traversal path with a total station survey tool, and a dead reckoning estimate of traversal generated through on-board sensing. Variation of plow depth between different trials yielded results which reveal the effects of plowing upon control authority.

3.1 Steep Ascent

Early qualitative testing developed general understanding of the capabilities of a tracked, low-slung rover. Discovery of a loose, 35° slope for testing pushed rover operations to discover locomotive limitations. For ascent, testing involved repeated ascents of slopes, recording video and survey position of rover progress for observation and analysis.

(a)



(b)

Figure 4: (a): Icebreaker's actuated plow. The box contains the motor and pinion for actuation, with the tube performing the actual plowing. (b): Tip of the plow, used to penetrate the soil surface.

3.2 Point Turning with Plow

For point turning, the rover starts facing perpendicular to the slope, and is commanded to perform a full-speed point turn, turning to face downhill, and then facing side-slope in the opposite direction. The rover executes a 180° turn, with any movement down-slope a result of slip. The rover at the starting position for a trial can be seen in Figure 5a.

3.3 Linear Descent with Plow

For linear descent tests, slip causes the rover to descend faster than predicted by the dead-reckoning model, with slip the disagreement between the expected and surveyed traversal distance. In order to test linear descent, the rover starts on a 38° slope used in descent testing, facing down-slope similar to Figure 5c. The rover is then commanded to travel at full speed until it completes a marked 10 m descent. Thus, the rover's actual descent consistently moves 10 m down-slope.

3.4 Plow Testing and Slip Calculation

Slip is unintended down-slope motion, not resulting from commanded motion. In order to accurately track and detect slip, testing employs a robotic total station. This device is a survey gun integrated with a pan-tilt mechanism. The survey gun localizes and tracks a 360° survey reflector, shown in Figure 6. By attaching the reflector to the front of the rover, as can be seen in Figure 5a, the total station accurately samples the rover's position at 2 Hz. In addition to the data from the survey data, the rover internally records roll, pitch, yaw-rate, and velocity commands at 2 Hz.

Using the recorded data, slip calculations occur using Equation 4. Summing the distances between position samples, as shown in Equation 7, gives actual distance traveled. Dead reckoning is performed by using the model shown in Figure 7, which leads to Equations 5 and 6 to translate rover commands into rover velocities [16]. The ideal distance traveled can then be found using Equation 8.

$$d_{slip} = d_{measured} - d_{ideal} \tag{4}$$

$$v_y[n] = \frac{v_l[n] + v_r[n]}{2} \tag{5}$$

$$\omega_z = \frac{v_r - v_l}{w} \tag{6}$$

$$d_{measured} = \sum_n \sqrt{(x[n] - y[n-1])^2 + (y[n] - y[n-1])^2 + (z[n] - z[n-1])^2} \tag{7}$$

$$d_{ideal} = \sum_n v_y[n] * (t[n] - t[n-1]) \tag{8}$$

Since the rover performs a point turn for each trial, no down-slope translation can occur in the ideal case. Thus, any down-slope movement of the rover measured by the

Figure 5: Sequence of rover orientations, showing a single trial of the turning test. For reference, the orange reflector, shown more clearly in Figure 6, is mounted towards the front of the rover.

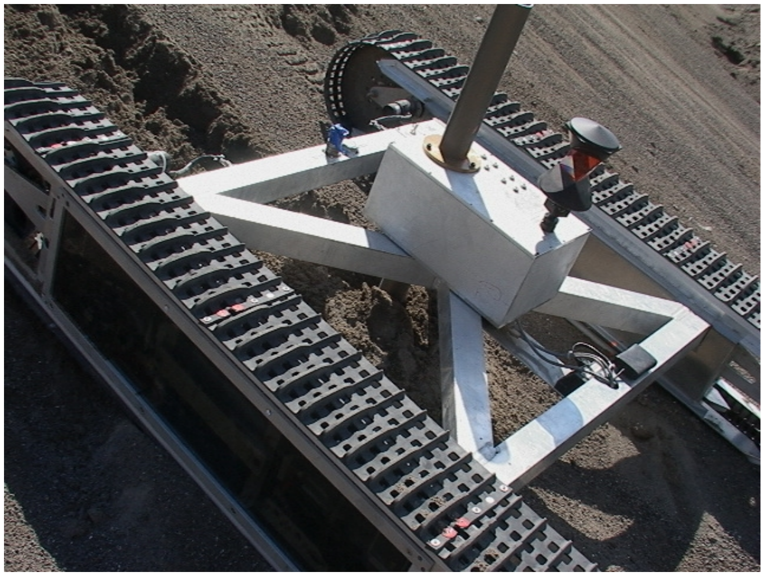


Figure 6: Close-up of rover, with the orange survey reflector visibly mounted on the plow enclosure. The reflector enables the total station to track and record the rover's position during maneuvers.

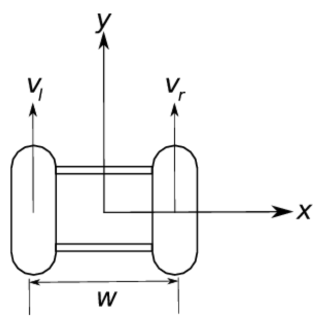


Figure 7: Diagram of simple skid-steer motion model used in dead-reckoning estimates.

total station turns out to be slip by definition. In this case, the internal dead-reckoning model is unnecessary. This results in Equation 4 reducing to Equation 7.

3.5 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 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 0.076 m below the surface was 4.95%. At a depth of 0.152 m the soil moisture content rose to 21.3%.

Bulk specific gravity of testing site terrain was 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 on two different models. The Surveyor model estimates an upper bound of 35° - 37°, while the Apollo model estimates an upper bound of 30° - 50°. Icebreaker's testing regolith had a friction angle of 52.6°. See Figure 8 for soil size comparison [12].

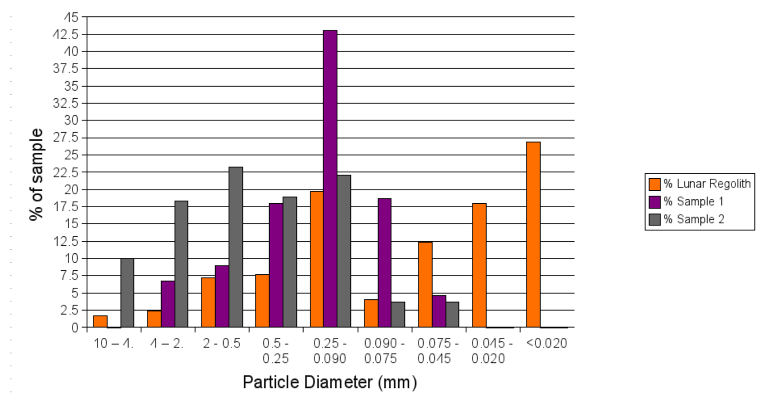


Figure 8: Comparison of particle diameters between Lunar soil samples, and local testing site samples.

4 Results

4.1 Steep Ascent

Control authority is the ability of a vehicle to drive an intended trajectory. It can be limited on steep slopes by traction, actuator torque, and orientation. Icebreaker is not limited by torque or longitudinal soil traction and will steadily climb the line of steepest ascent/descent on slopes at an angle-of-repose of 35° with sufficient surface strength to support traction. It can ascend these slopes repeatably, although slip occurs due to high speeds or acceleration.

Control authority is limited on these steep slopes, however, because the rover is unable to turn in place regardless of initial orientation. As the tracks rotate soil surface fails, producing 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 comply to maximize ground contact. This increases ground pressure, decreases traction, and introduces dynamic effects on 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. For Icebreaker, however, ground compliance remains a relatively minor complication.

4.2 Point Turning with Plow

In-place turning was tested with 0 m, 0.07 m, and 0.2 m plow depths. Figure 9 shows the accumulated slip for each trial, with the plot of a linear regression across all trials ($r^2 = 0.94$). Comparing mean accumulated slip between 0 m and 0.2 m plow depths, results show a reduction in slip by a factor of 3.2. Figure 10 shows the calculated slip-rates as a function of down-slope angle at each individual plow depth. In Figure 10, yaw angle is taken as an absolute value - zero degrees corresponds to facing down-slope, while ninety degrees corresponds to facing side-slope in either direction. For these plots, least-squares fit of an exponential decay is also shown to emphasize the trend in slip rate for each plow depth.

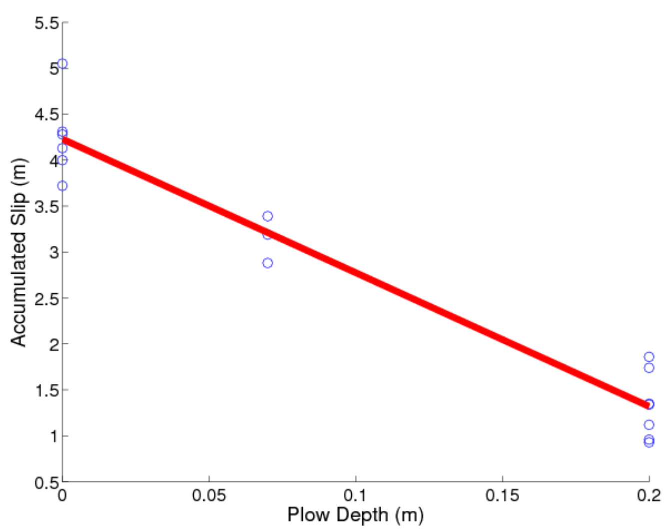
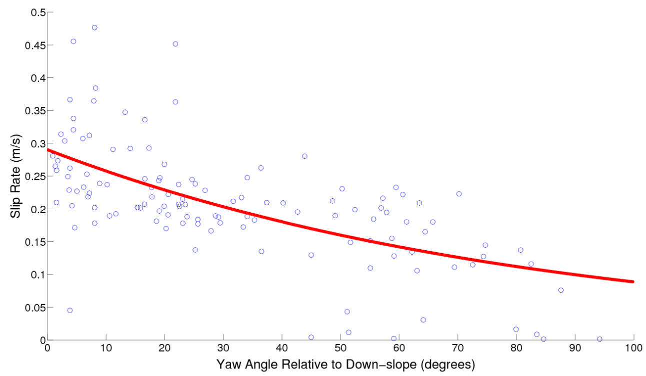
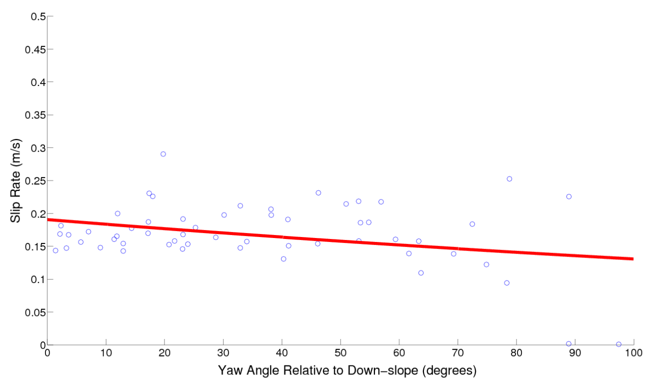


Figure 9: Accumulated slip during turning maneuvers with various plow deployments.



(a)



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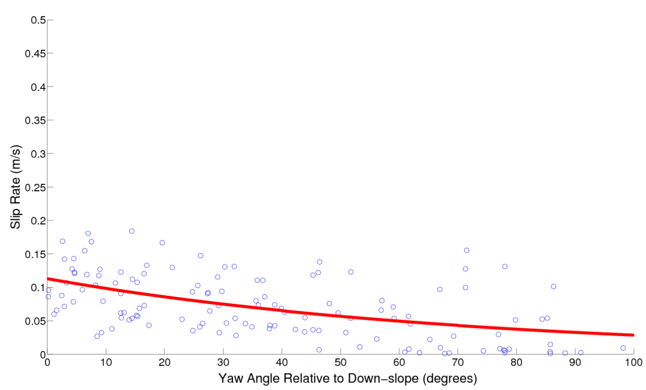

(c)

Figure 10: Slip rate vs. yaw angle for point turning with plow depth set to (a): 0 m (b): 0.07 m (c): 0.2 m

4.3 Linear Descent with Plow

For linear descent, at least three trials each were performed with the plow depth set to 0 m, 0.07 m, 0.14 m, and 0.2 m. Figure 11 records accumulated slip for each trial, with the plot of a linear regression over all trial data ($r^2 = 0.89$). Comparing mean accumulated slip at 0 m and 0.2 m plow depths, the plow reduces slip by a factor of 19.6 in linear descent.

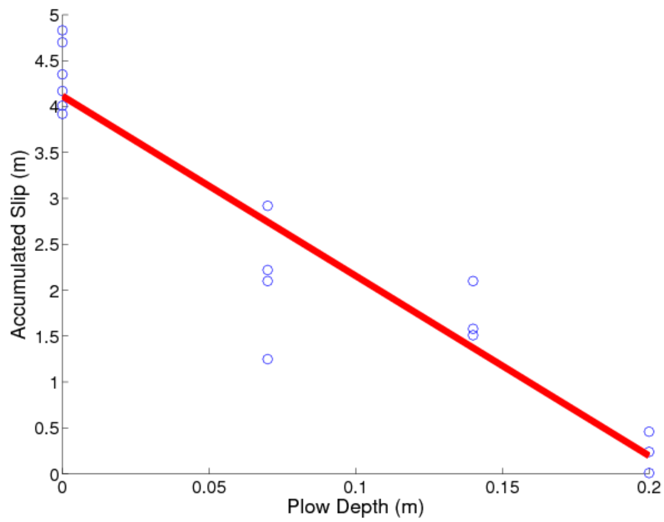

Figure 11: Slip rates during linear descent with various plow depths.

5 Discussion

Icebreaker's design creates consistent, capable locomotion, presenting unprecedented crater climbing. In ascent, results highlight advantages of tracked locomotion and a low center of gravity. Excessive slip in turning and limitations due to ground compliance limit full control authority during ascent of steep slopes. For descent, plowing significantly reduces slip and improves control authority on steep, unconsolidated slopes.

For turning maneuvers, plowing reduces the amount of down-slope slip the rover undergoes, as well as resisting landslides caused by rover motion. A large spike in slip-rates where $-20° < \theta < 20°$ is shown in Figure 10a, reaching almost $0.5\frac{m}{s}$ in some cases. These spikes correlate to these landslide events. Exponential decay curves fitted to the instantaneous curvature data highlight the impact of plowing. The landslide events are clearly highlighted in Figure 10a through the inflection of the curve, while Figures 10b and 10c show significantly flatter curves. These landslides correspond to surface failures predicted by Equation 3, with examples of such events in Figure 12.

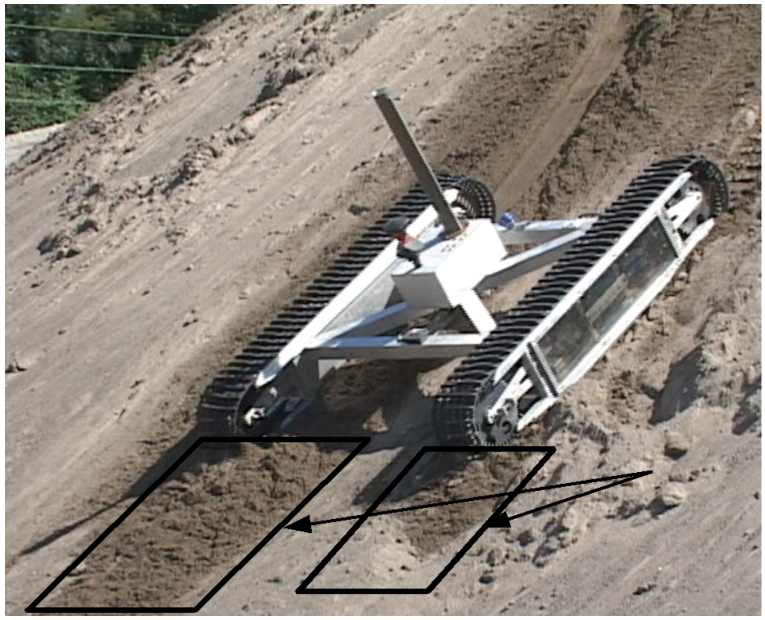

Figure 12: Highlighted regions show examples of soil surface failures during motion.

For linear descent, slip works to force the rover to descend faster than commanded, which not only causes the rover to descend further than desired, but also to increase stopping distance. Descent attempts with no plow engaged where commanding a stop results in uncontrolled slides to the bottom of the test slope. Plowing creates a resistive force which counteracts slip, returning control authority and shortening stopping distance. Engaging the plow reduces slip by more than an order of magnitude. Accumulated slip shows strong linear correlation between plow depth and slip rate, as expected given Equation 3.

6 Conclusions

Testing validates this rover configuration for crater ascent/descent. Icebreaker's design combines tracked locomotion, a wide stance, and a low center of gravity. Testing results highlight the capability of the rover to ascend and descend steep, unconsolidated slopes. Tracks provide consistent traction and high flotation, preventing foundering. Having a low, wide stance stabilizes the rover on steep surfaces, preventing tipover. The rover configuration achieves unprecedented traversal of steep, unconsolidated slopes.

Tracked locomotion drives the rover's ability to ascend and descend crater slopes. However, one significant issue with track implementations related to side-slope navigation challenges the design. Tracks remain attached to the vehicle through tension between the two main idlers, as seen in Figure 2. When traversing side-slopes, gravity

Figure 13: Plow engaged during a linear descent, clearly displaying the trench resulting from plowing.

applies force transverse to the rover's motion. This results in pulling tracks off the vehicle, disabling motion. In order to solve this issue, guides which contain the track edges would be integrated to hold the tracks in place. Merits of tracks are apparent, although no space-rated track designs currently exist.

Control authority on steep, unconsolidated slopes improves significantly through the use of a plowing device. In particular, slip due to landslide events is completely eliminated from $-20^\circ < \theta < 20^\circ$ of down-slope, and other forms of slippage are significantly minimized as well. Furthermore, empirical evidence confirms the expected linear relationship between slip rates and plow depth.

Several concepts and development directions of rover-based plowing can extend the work presented here. The plow currently operates open-loop, penetrating to a commanded depth and remaining static for the duration of a maneuver. Since subsurface soil does not remain uniform throughout a slope, this results in variations in the amount of resistive force provided through plowing. More efficient plowing, with tighter control of slip, could be achieved through closing the loop between plow depth and slip rates. Exploring alternate plow designs, with possibilities such as directionality of plowing and more efficient plow shapes, also promises potential improvements. Most interesting, however, is the concept of developing additional uses for the plow.

Integrating sensors or tools into the plow, such as a cone penetrometer, can provide additional functionality in a single device. Cone penetrometers provide in-situ measurements of soil characteristics. Measuring important soil properties such as soil void ratio, specific gravity, penetration resistance and surface strength can provide data about soil properties on lunar crater walls [3]. Other tools and sensors, such as drills or tuned laser diodes, could even help turn a plow into a mobile subterranean lab. Further science may be possible with the side-effects of plowing. As seen in Figure 13, plowing produces deep trenches during descent, which expose sub-surface soil. Sensor placement can potentially benefit from this, studying soil exposed through plowing. With these sorts of efforts, a plow can move from a locomotive aide to an integral part of a science mission.

Plowing makes controlled descent into craters possible, allowing stable travel on unconsolidated slopes. Plowing provides greater than an order-of-magnitude improvement in slip control with only one additional degree of freedom. The gains of plowing to control descent cannot be realized through traditional traction methods or path planning schemes, and can only be gained by reaching under the surface. Furthermore, the technique utilizes a straightforward and well-understood phenomenon, minimizing complexity in understanding and control schemes. However, plowing requires forceful actuation to succeed, relying on penetrating significantly into lunar regolith. Designs must carefully consider best practices for penetrating lunar regolith without causing undue harm from dust or abrasion. In addition, plowing can place additional strain on other actuators attempting to move the rover if placed too deeply. Plowing provides considerable benefits when correctly designed and integrated.

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