Plowing for Controlled Steep Crater Descents

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Abstract

Controlling slip is crucial to reliable descent of steep unconsolidated slopes such as those found in lunar craters. The ability to enter these craters provides opportunities to explore potential in-situ resources, such as water ice. We present a rover prototype with a novel, actuated, omni-directional plowing device and control method for maneuvering on steep slopes. Data from field experiments show reliable control during descent on loose sand slopes up to 40°, with twenty-fold reduction in downhill slip and a threefold reduction in slip during point turns. In particular, the data indicates that plowing eliminates slip caused by shear failure created in angle-of-repose material.

1. Introduction

Discovering water ice and other important volatiles on the lunar surface drives attempts to explore the interior of lunar craters. Volatile trapping craters may range in size from a few tens of meters to tens of kilometers in diameter. Plans for extended human presence on the lunar surface benefit significantly from in-situ resource utilization [14]. With evidence that cold traps located in craters at the lunar poles potentially contain water ice [1, 8, 5, 20] controlled descent of crater slopes is a keystone to exploring these resources.

Models for lunar craters estimate unconsolidated regolith slopes with a 30 - 40° angle-of-repose [6, 7]. These slopes exhibit fluid-like flows of soil, resulting in an uncontrolled "surfing" descent. Theory suggests that for loose, granular soil, strength lies under the surface, not on, the surface [18, 21]. In order to explore rover technologies for this regime of locomotion, Icebreaker, a prototype rover is presented. The primary objective of this rover is to explore and develop concepts of locomotion for crater descent. Research pushes technologies and configuration requirements for planetary rovers intended to descend steep crater walls. The primary innovation is the use of plowing to control descent.

2. Rover Design

Goals of steep crater navigation come from a mission proposal to send a small, low cost rover as a secondary payload opportunity [3]. The mission framework called for exploration of lunar craters with little available space; a compact, capable rover could fit the requirements, but costs would require a rover capable of landing outside a crater to descend inwards. These limitations drive the design towards the current form.

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. Components like batteries and computers can be placed within the tracks, keeping mass close to the ground. 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 and steady descent and features a low center of gravity, high traction, and low ground pressure.

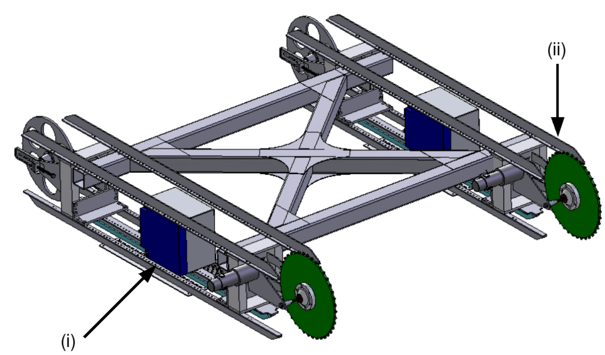


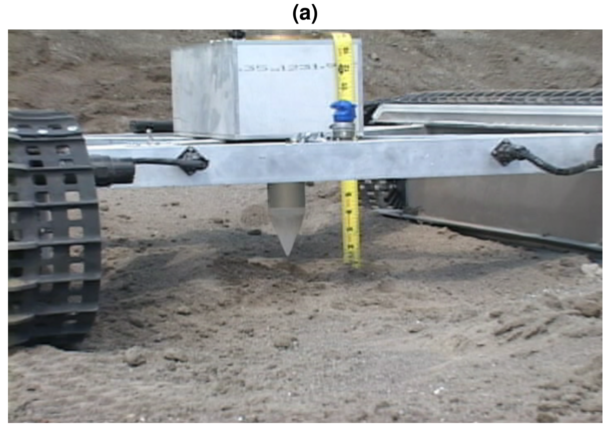
Figure 1. Icebreaker chassis design. (i) Internal volume for components (ii) Tracks for locomotion.

The rover chassis, as seen in Figure 1, shows the chassis design of the rover. The rover measures 1.4 meters long, 1.1 meters wide, and 0.3 meters tall. The chassis provides a rigid frame to which tracked side-frames are attached. The frame maintains the simplicity of design, reducing weight and complications arising from an articulated or actuated frame. The side-frames provide an internal volume to contain components for robot operation. Instead of idler wheels along the length of the track, Teflon guide bars provide low-friction support without using any significant volume. The chassis provides a low center of gravity to prevent tipping on steep slopes, and a wide, long, and low stance for stability in deep terrain. The tracks provide locomotive force with high flotation, low ground pressure, and increased surface area. These characteristics allow the rover to grip terrain, bridge surface irregularities, and limit rover sinkage.

Plowing refers to the technique of driving part of the rover below the surface of the soil beneath the rover, using the subsurface strength to reduce slip and resist surface soil motion. In order to accomplish this, an actuated plow was developed and installed on the rover. The plow consists of a hollow steel pipe 0.15 m in diameter tipped with a conical lexan nose. Since the plow's cross-section is circular, the plow presents omnidirectional 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.

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 allowed the rover to drive straight lines and point-turns, minimizing any negative impact the plow would otherwise have upon intended motion. Plow actuation allows the plow to penetrate 0.23 m into the ground via a rack and pinion mechanism. The plow can be seen in Figure 2. Testing revealed remarkable maneuverability on steep, loose terrain.

(a)



(b)

Figure 2. (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. Experimental Design

Icebreaker's testing regime aims to prototype and support new technologies for safe lunar crater descent. Testing provides empirical evidence to support the technologies and concepts developed. For plowing, testing highlights the impact plowing has on control authority while descending, and provides indications as to future development of the plowing concept. This involves two tests to measure slip while performing basic maneuvers on lunar-like soil.

For the purposes of these tests, tests consider slip over both accumulated and instantaneous cases. Slip is considered to be unintended motion downhill, which occurs while executing desired maneuvers. Accumulated slip provides a macroscopic view with strong evidence for the impact of plowing upon control authority. Instantaneous slip provides insight into causes of increased slip

Testing explores slip under two different motions: linear descent and point turns. In both cases, rover movement causes soil flows which produce significant slip, confounding the rover's motion. By varying the plow depth between 0 m (disengaged), 0.07 m, 0.14 m, and 0.2 m, the effects of plow depth on slip rates is explored. 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.

For turning tests, 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 3a.

For linear descent tests, the rover begins facing downslope, and is commanded to travel at full-speed until it completes a 10 m descent. In this case, 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.

3.1. Slip Calculation

Slip is unintended motion down-slope, 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° reflective survey crystal. By attaching the crystal to the front of the rover, as can be seen in Figure 3a, the total station records the rover's motion in great detail. In addition to the data from the survey data, the rover

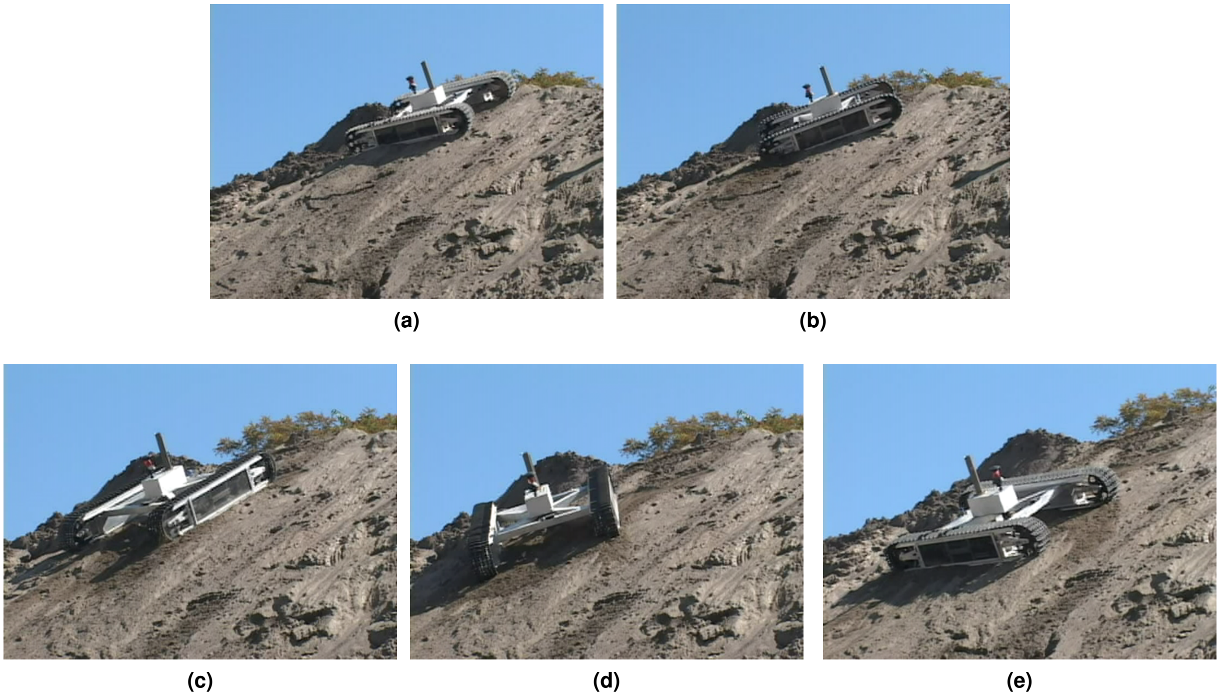


Figure 3. Sequence of rover orientations, showing a single trial of the turning test. For reference, the orange crystal is mounted towards the front of the rover.

internally records roll, pitch, yaw-rate, and velocity commands for a simple internal dead-reckoning model.

With this data, slip calculations for turning tests simplify to a trivial calculation. 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 total station turns out to be slip by definition. In this case, the internal dead-reckoning model is unnecessary. Accumulating all the down-slope translation recorded by the total station is the only step required to calculate slip.

For linear descent, slip calculations require only slightly more calculation. Since the rover descends along the maximum gradient, and performs only a straight translation, the motion model can be simplified to a single point, moving at $v_{rover} = \frac{v_{lefttrack}+v_{righttrack}}{2}$. By propagating the rover forward with this velocity, and comparing this to the surveyed distance traveled, slip is calculated using a minimal amount of sensor data.

4. Results

In-place turning was tested with 0 m, 0.07 m, and 0.2 m plow depths. Figure 4 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. Figures 5, 6, and 7 show the calculated slip-rates as a function of yaw at each individual plow depth.

For linear descent, at least three trials were performed

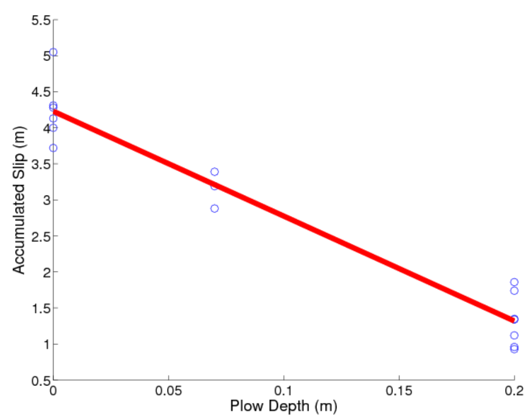


Figure 4. Accumulated slip during turning maneuvers with various plow deployments.

with the plow depth set to 0 m, 0.07 m, 0.14 m, and 0.2 m. Figure 8 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. Results of both tests are summarized in Table 1.

5. Discussion

Plowing significantly reduces slip and improves control authority during descent on steep, unconsolidated slopes. Subsurface strength comes from Control authority is the ability of

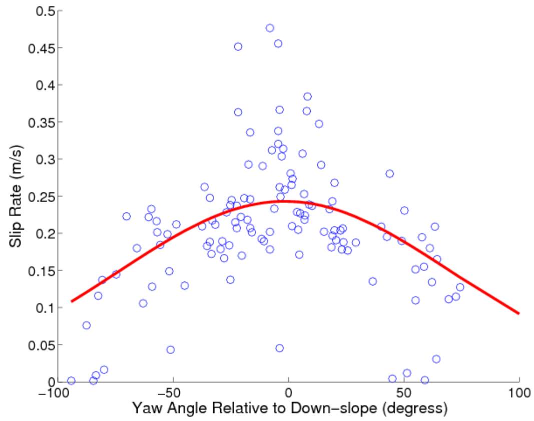


Figure 5. Slip rate vs. yaw angle for turning with no plow engaged.

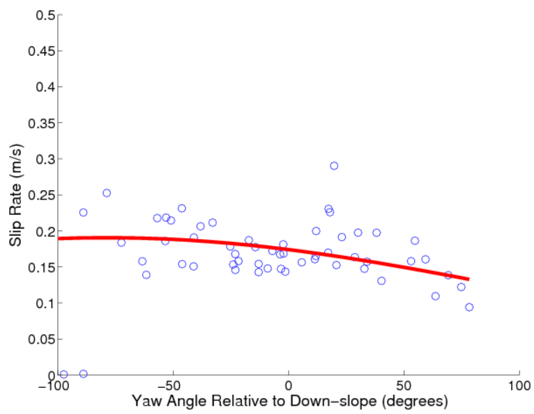


Figure 6. Slip rate vs. yaw angle for turning with plow 0.07 m deep.

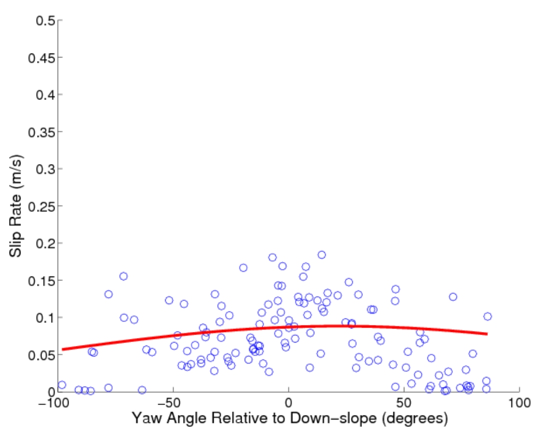


Figure 7. Slip rate vs. yaw angle for turning with plow 0.2 m deep.

Table 1. Comparison of total slip at no plow (0 m) and full plow (0.2 m)

Experiment	Slip (no plow)	Slip (full plow)	Factor Reduction
Linear Descent	0.43 m	0.02 m	19.58
Point Turns	4.25 m	1.33 m	3.20

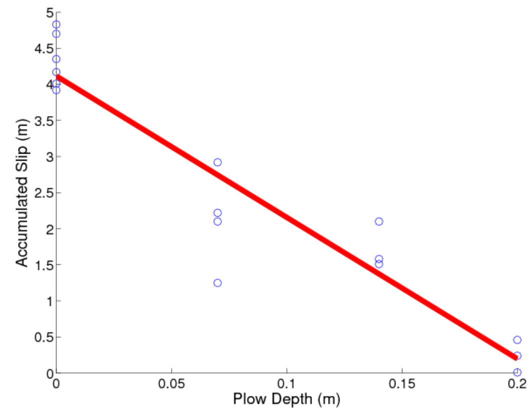


Figure 8. Slip rates during linear descent with various plow depths.

a vehicle to drive an arbitrary path. It can be limited on steep slopes by surface strength failure, traction, actuator torque, and orientation. The Icebreaker rover design 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°.

Control authority is limited on these steep slopes, however, because of shear failure, which creates landslides. For a uniform layer of granular soil, the normal stress on a element of soil can be approximated by Equation 1, where σ_v is vertical stress, z is depth beneath the surface, and γ is unit weight. This states that vertical stress is linearly related to depth.

$$\sigma_v = z * \gamma \tag{1}$$

The Mohr-Coulomb Criterion shown in Equation 2 states that shear strength of granular soil linearly relates to the normal stress, where τ is shear strength, σ is stress, and ϕ is friction angle. Combining Equations 1 and 2 results in Equation 3, which shows a linear relationship between shear strength and soil depth [18]. Thus, it is expected that at the soil surface, landslides occur due to the low shear strength, while greater strength resides deeper in the soil. An example of these landslide events appears in Figure 9.

$$\tau \propto \sigma * tan(\phi) \tag{2}$$

$$\tau \propto z * \gamma * tan(\phi) \quad (3)$$

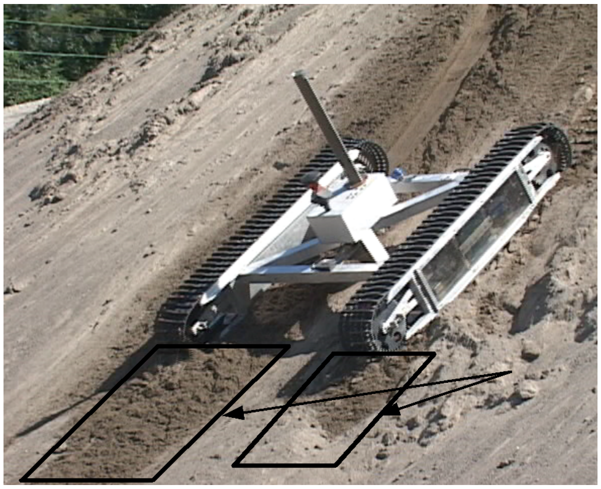


Figure 9. Highlighted regions show examples of fluid-like flows of the soil surface layer forming during motion.

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. Video from early qualitative runs show 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, allowing the rover to regain control authority and lower stopping distance. Engaging the plow reduces slip by more than an order-of-magnitude, with a strong linear correlation between plow depth and slip rate.

Figure 10. Plow engaged during a linear descent, clearly displaying the trench produced as a result of plowing.

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 5, reaching almost $0.5\frac{m}{s}$ in some cases. These spikes correlate to these landslide events. Gaussian curves fitted to the instantaneous curvature data highlight the impact of plowing. The landslide events are clearly highlighted in Figure 5 through the inflection of the curve, while Figures 6 and 7 show significantly flatter curves.

6. Conclusion

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

Plowing makes controlled descent into craters possible, allowing stable travel on unstable slopes. The mechanism for plowing keeps complications to a minimum, providing greater than an order of magnitude improvement in slip control with a only one additional degree of freedom. The gains of plowing 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, or can put the rover in untenable positions if the plow breaks. Plowing provides considerable benefits when correctly designed and integrated.

Several concepts and development directions of rover-based plowing can extend the work presented here. Closed-loop control around plow-engagement promises more efficient use of plowing and tighter control of slip during descent, allowing efficient and controlled traction consistently. 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.

By integrating sensors or tools into the plow itself, such as a cone penetrometer, can provide additional functionality in a single device. Cone penetrometers provide non-invasive, accurate 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 [2]. Other tools and sensors, such as drills or tuned laser diodes, could even help turn a plow into a mobile subterranean lab. With these sorts of efforts, a plow can move from a locomotive aide to an integral part of a science mission.

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