Plowing for Rover Control on Extreme Slopes

David Kohanbash, Scott Moreland and David Wettergreen

Abstract Planetary rovers are increasingly challenged to negotiate extreme terrain. Early destinations have been benign to preclude risk, but canyons, funnels, and newly discovered holes present steep slopes that defy tractive descent. Steep craters and holes with unconsolidated material pose a particularly treacherous danger to modern rovers. This research explores robotic braking by plowing, a novel method for decreasing slip and improving mobility while driving on steep unconsolidated slopes. This technique exploits subsurface strength that is under, not on, weak soil. Starting with experimental work on Icebreaker, a tracked rover, and concluding with detailed plow testing in a wheel test-bed the plow is developed for use. This work explores using plows of different diameters and at different depths as well as the associated braking force. By plowing the Icebreaker rover can successfully move on a slope with a high degree of accuracy thereby enabling science targets on slopes and crater walls to now be considered accessible.

1 Introduction

The robotic exploration of planetary bodies requires rovers that can safely explore a variety of environments and have the ability to reach points of scientific interest. Rovers significantly expand the possible exploration areas and increase the scientific and programmatic return from a mission. The surface of the moon and planets such as Mars are covered in fine and unconsolidated regolith making mobility considerations of utmost importance[7]. There are many craters and steep slopes that are also

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covered in this fine and unconsolidated regolith. The ability to traverse steep slopes, funnels, and holes becomes even more compelling in the case of Mars where there is now evidence of new deposits forming on the side of crater walls (Figure 1) [10] and in the case of the moon with resources in permanently shadowed polar craters. Many of these crater walls have slopes that exceed 25 degrees [1] [5].

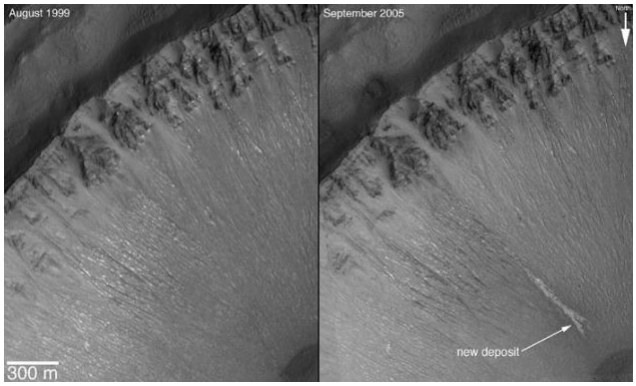


Fig. 1 New deposits found on a crater wall in Centauri Montes [10].

1.1 Background

In this work a plow mechanism is tested both on a rover named Icebreaker as well as in a wheel test-bed to throughly characterize how a plow can be used for increased control authority on a slope.

The ”plow” is a dagger like rod that is driven into the ground by a robot to create a braking force by exploiting the subsurface soil strength (Figure 2). This braking force is used to counter downhill forces in order to minimize slip (undesried/uncommanded downhill motion). The plow is a circular rod located at the center point of the robot to facilitate turning. This is a mechanical analog to a climbers use of an axe or pole to arrest or control a downhill slide. The plow on the rover is actuated using a rack and pinion and has a lexan tip to help the plow pierce the ground to minimize vertical plow forces (Figure 3).

It is generally recognized that the interaction of the rover and the terrain is complex and difficult to model. In addition, standard models do not work in very unconsolidated material with low moisture levels [15]. Prior work with model based terrain controls have problems with accurately modeling the terrain and seek better methods to simulate the wheel-terrain interaction [2][6]. For these reasons having a device that is purely reactive and not dependant on possibly inaccurate models is important.

Fig. 2 Icebreaker's actuated plow. The box contains the motor and pinion for driving the plow into the ground[17].

Fig. 3 Icebreaker actuated plow. Conical lexan tip is used to penetrate into the ground[17].

1.2 Prior Research in Plowing[8]

In farming tines that are similar to the plow used in this work have been studied. It is important to note that most tools that interact with the ground have been designed more on the basis of field experience than on scientific knowledge since soil-tool interaction is not well defined and quantified [12]. It has been found that soil moisture and shear strength have the largest impact on the soil forces, and at small speeds, the effect of speed can be neglected [3]. The disturbance pattern in the soil has been shown to be repeatable in a wide range of materials and soil moistures for a given tine design[14].

There are two distinct depths that need to be considered when analyzing the plow forces. Plowing above the critical depth results (Figure 4) in brittle failure, which does not provide a significant resistance force to the plow. This failure is deemed crescent failure where the disturbed soil is pushed to the sides, in front, and upward. Plowing below the critical depth results in the surrounding soil compacting in the direction of motion, thereby providing the subsurface strength that is needed for plowing. This is called lateral failure (Figure 5) [3]. This means that in order to have significant subsurface strength the plow depth must be deeper than this critical depth.

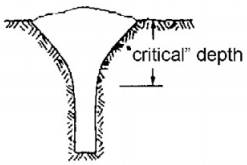


Fig. 4 Critical depth in plow track [3].

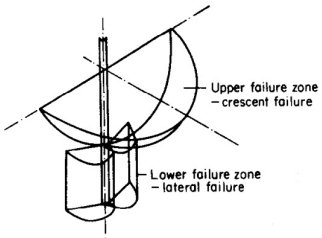


Fig. 5 Both soil failure modes of a tine are shown [4].

2 Rover Testing

Icebreaker is a prototype rover designed to traverse into steep planetary craters. The rover is 70.4kg with 47.9% of the weight to the left and 55.0% to the rear. It is 1.1 meters wide and 1.4 meters long with a track width of 15.5cm. The top of the rover deck is 22cm from the ground. It is a tracked rover since tracks can offer the best solution for operating over complex terrain. This is especially important for steep and loose slopes [13]. The chassis provides a rigid frame to which the tracks are attached and the plow is mounted. The plow is mounted 11cm from the center of the rover and is actuated to allow for easy plow adjustments (some work has been done creating a slip controller to dynamically adjust the plow). The tip of the plow has a lexan cone which is needed to help pierce into the soil and proceed with lowering the plow further into the ground. All of the electronics and batteries for the rover are contained within the track side frame. This helps the rover maintain a very low center of gravity at 13.2cm from the ground.

2.1 Experiment Design

Testing with Icebreaker was conducted at the Simulated Lunar Operations (SLOPE) facility at the NASA Glenn Research Center in Ohio. The SLOPE facility has a large sandbox of GRC-1 lunar simulant that is capable of tilting to 30 degrees. The soil is prepared using a standard method called T3 [16] to achieve conditions similar to the lunar terrain[11]. This process involves using a shovel to disturb and loosen the subsurface soil where the rover will be operating and then it is smoothed lightly using a rake to insure uniform conditions for the test. A Leica TCRA1103+ Total Station is used to track the rovers position with high accuracy in order to determine slip (Figure 6). There is also an adjustable load system and a load cell for conducting drawbar pull tests (Figure 7).

Fig. 6 Test setup with surveying instrument (on the left) and prism (bright spot) mounted on a rover at NASA GRC SLOPE facility.

Fig. 7 Drawbar pull rig with adjustable load at the SLOPE facility[16].

Four types of tests were conducted at the SLOPE test facility: decent, drawbar pull, cross slope, and point turns. A driving test on flat simulant was done to confirm that there is no bias between the tracks and to get the speed differential between commanded and actual drive distance. Before starting the tests it was qualitatively observed that the vehicle had minimal slip at around 17cm plow depth. In order to bound this testing was done at 14cm and 20cm plow depth and then at 7cm plow depth to bridge the gap from 0cm to 14cm in many of the tests. The plow used in this test is 5cm (2 inches) in diameter and the vehicle moved at 0.02m/s.

2.1.1 Descent

Descent tests were done with Icebreaker on a slope at 31 degrees (Figure 8) with plow depths of 0cm, 7cm, 14cm, and 20cm where 0cm is plow disengaged and 20cm is the plow fully embedded into the ground. This gives a clean comparison of vehicle performance and how the plow improves mobility.

Fig. 8 Descent test at 31 degrees.

2.1.2 Drawbar Pull

Drawbar pull tests were conducted with various loads at the four plow depths. For this test the drawbar pull rig at NASA Glenn Research Center was used. This rig allows for an adjustable load to be applied to the rover and for recording of vehicle position. A load cell was attached between the rover and the adjustable load rig. This helps us understand the braking force being applied by the plow to the rover (Figure 9).

Fig. 9 Draw bar pull test setup with lines going to a load cell and the variable load source.

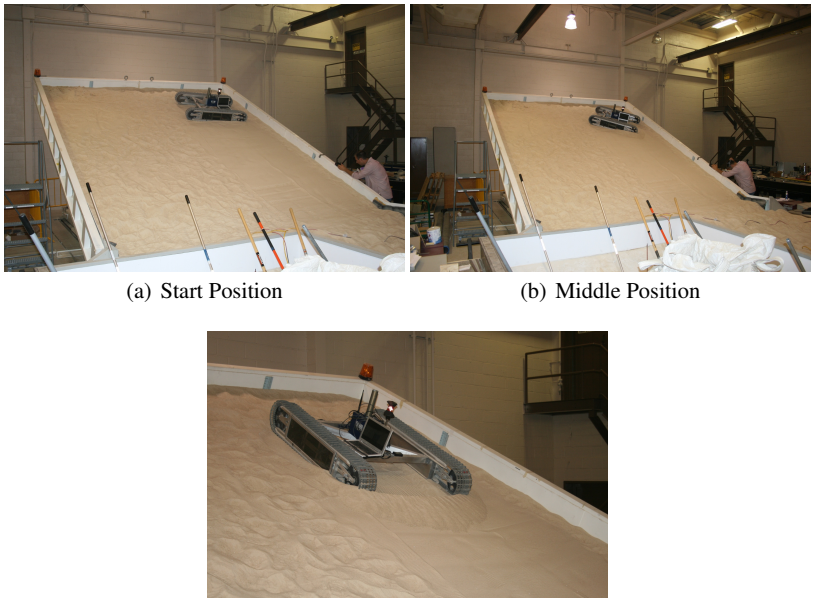
2.1.3 Cross slope

Cross slope tests were done at slope angles of 10, 15, 20, 25, and 30 degrees with no plow engaged (Figure 10). The plow was not used in this case since the primary benifit of the plow is downslope.

Fig. 10 Cross Slope test at 30 degrees.

2.1.4 Point turns

Point turn tests were done at slope angles of 10, 15, 20, 25, and 30 degrees for each plow depth of 0cm, 7cm, 14cm, and 20cm. Figure 11(a) shows how the rover is positioned to start a test, figure 11(b) shows the rover in the middle of a test as it is pointed at about 45 degrees, and figure 11(c) shows the position of the rover at the end of the test where it is pointed downhill.



(a) Start Position (b) Middle Position

(c) End Position

Fig. 11 Point turning test on 25 degree slope (clockwise rotation)

2.2 Experimental Results

2.2.1 Descent

Descent tests exhibit an improvement as can be seen from having no plow where the rover slipped about 27cm to when the plow is in the full 20cm depth and acts like a brake to fully counteract the slip and even slightly impede rover motion (Figure 12).

2.2.2 Drawbar Pull

In the drawbar pull tests results are consistent with what was observed in the slope tests. The deeper the plow is into the ground the greater the resistance to slip at a given force. This becomes interesting for the 20cm plow depth where at an applied force of 100% vehicle weight the rover still has trivial slip (Figure 13).

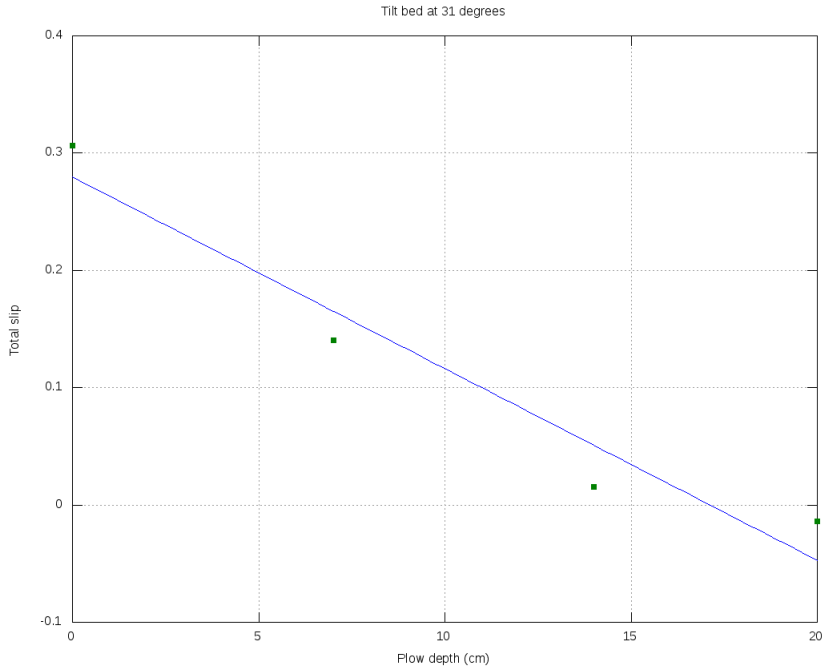


Fig. 12 Descent tests on a 31 degree slope at 4 plow depths.

2.2.3 Cross Slope

The tracked rover demonstrates excellent cross slope abilities. Even at a 30 degree slope there is only 15% downhill slip (Figure 14).

2.2.4 Point Turns

Point turning with the plow also has a tremendous influence (Figure 15). While with full plow depth all of the turns had less than 10cm of slip the effects at the 30 degree maximum slope are the most telling. At 30 degrees with no plow the vehicle slipped 0.58 meters, however with the plow fully engaged the slip was only 0.077 meters.

2.3 Summary

The addition of the plow to the rover can clearly be seen to benefit mobility, above what can be achieved with just tractive ability. Using the plow reduces slip in a

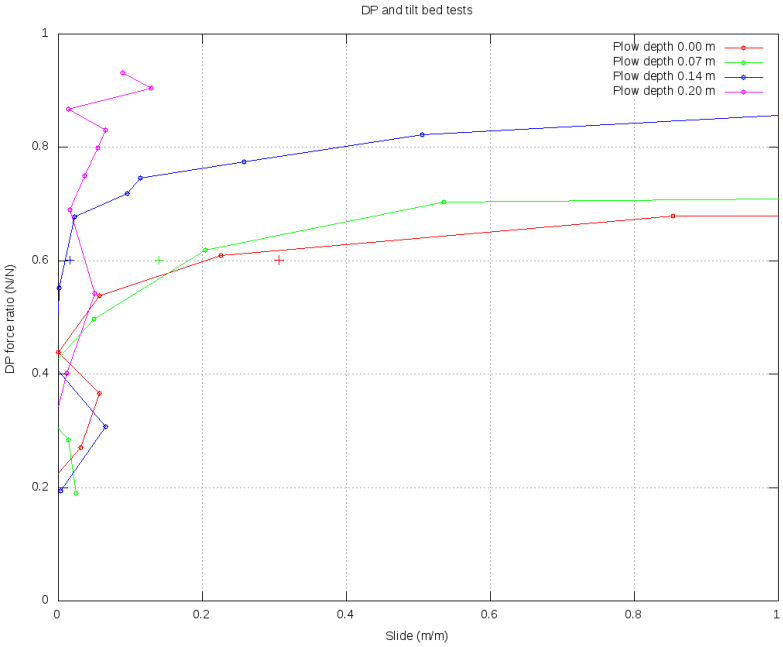


Fig. 13 Drawbar pull with the plow at 4 depths. + points represent the slip values from the descent tests.

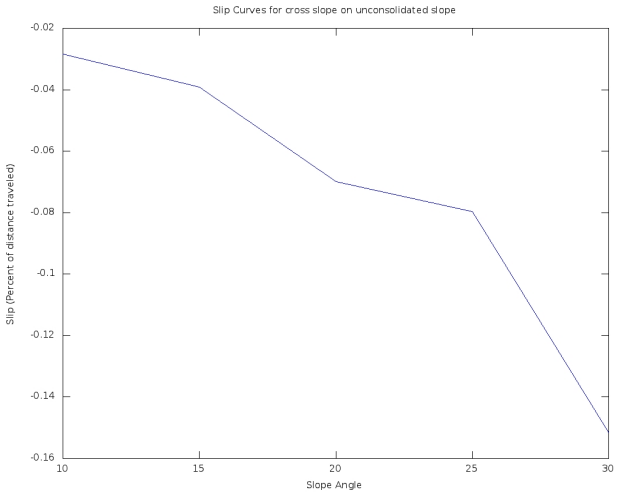


Fig. 14 Cross slope plots. Note the y axis has a range of 0.18 percent

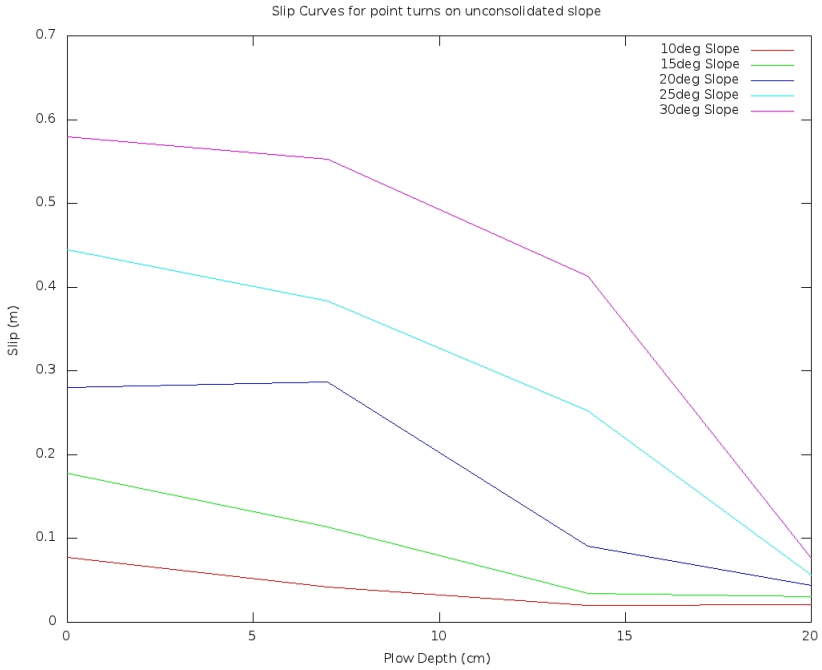


Fig. 15 Point turns slip curves.

variety of situations that are important when traversing on extreme slopes. This is important as since mission planners can now develop plans for operating on steep slopes in order to meet objectives and to reach areas of interest.

3 Plow Analysis

In addition to rover testing this research examines the plow as a mechanism in order to develop the tool and to create a guide that future developers can use to design and evaluate the plow. This work focuses on the different variables that affect plow design independent of the vehicle.

3.1 Experiment Design

In order to quantify the plow performance, tests were conducted in the wheel test-bed at CMU [9]. These tests are designed to look at how the plow performance scales as the plow diameter changes and with plow depth.

The wheel test-bed has a sandbox filled with the GRC-1 lunar simulant that is prepared in a similar fashion to the large sandbox at the Glenn Research Center SLOPE facility before each test. In the sandbox a spade is used to loosen all of the subsurface sand and then it is lightly smoothed with the blade of a small dustpan. The wheel test-bed has a motor that can pull the plow at a constant velocity of 2cm/s and record the forces on the plow in the direction of travel with an ATI Delta Transducer six axis force torque sensor. Tests were conducted with plows of 1.27cm (0.5 inch), 2.54cm (1 inch), and 5cm (2 inch) diameter. A 7.62cm (3 inch) plow was tested, however the forces were too large for the calibration range of the load cell. All of the plows were tested at 2.5cm, 5cm, 7.5cm, 10cm, 12.5cm, and 15cm depth. A depth of 20cm was attempted, however the forces exceeded the range of the load cell.

3.2 Experimental Results

Testing done in the wheel test-bed is very informative and helps us understand how the plow works. The results can be seen in figure 16. As expected increasing the plow diameter and/or increasing the plow depth showed an increase in braking force. Since all of these plows had a critical depth less than 2cm a braking force is achieved at the shallowest depth tested of 2.5cm. For each plow the force at 15cm depth increases 10 fold as shown in table 1. This plow testing is important and useful for engineers developing plowing systems.

Plow Diameter	Percent Change
1.27cm	33
2.54cm	45
5cm	56

Table 1 Percent force increase from 2.5cm to 15cm plow depth for each plow diameter

One of the basic ideas that aligns with theory is that all of the track patterns formed from the plow cutting through the sand were an identical shape as can be seen in figure 17. The depth of the chevron shaped mark from the plow is roughly the critical depth 2. There is also a considerable amount of bulldozing at the front of the plow (Figure 18).

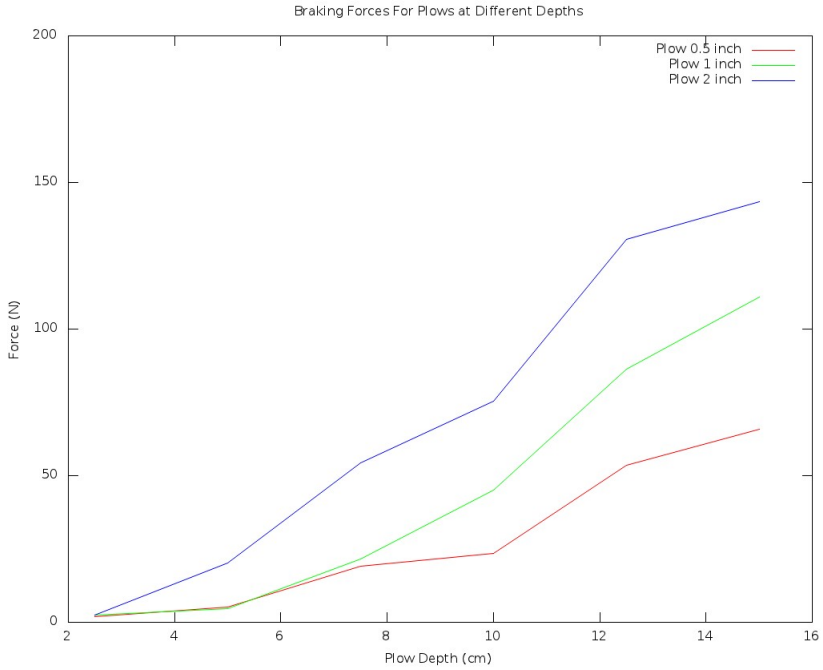


Fig. 16 Force (N) for a given plow diameter at different depths. NOTE: Plow diameter is in inches.

Plow Diameter	Critical Depth
1.27cm	2.26cm
2.54cm	3.33cm
5cm	4.5cm

Table 2 Critical depths for each plow tested determined experimentally.

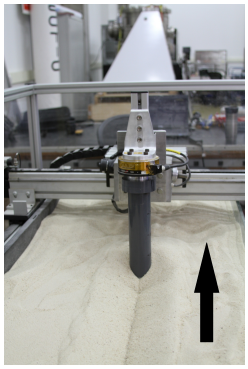


Fig. 17 Shape of path created by 5cm (2 inch) diameter plow. Black arrow shows direction of plow motion.

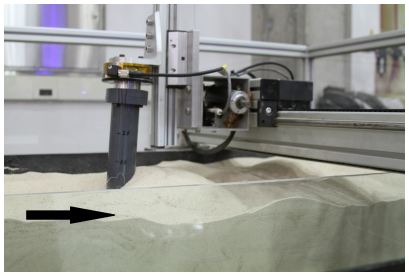


Fig. 18 Bulldozing at end of 5cm (2 inch) diameter plow. Black arrow shows direction of plow motion.

4 Conclusion

This research affirms quantitatively that plowing can be used in practice for control on extreme planetary surfaces that defy tractive descent. This work has shown a 7.5 fold reduction in slip when using the plow on 30 degree slopes as well as a complete reduction of slip on straight downhill descents on slopes up to 31 degrees. A new understanding of the plow teramechanics is now known based on a thorough review of farming literature and tine research. The trade offs of plow depth vs plow size has been explored. This gives the ability to design a plow and know what the braking forces will be. By using the plow rovers now have the ability to traverse into steep unconsolidated craters, canyons, funnels, and holes to explore both the slopes and the bottoms.

4.1 Future Work

There are many ways that this work can be extended and future directions for this work to follow. I think the most important one is to further develop a reactive plow controller based on on-board slip estimation. The ability to estimate slip on the fly and react is critical to steep slope navigation. Initial results with these type of controllers look very promising. This work has focused on a uni-directional plow however there is a lot of work that can be done with a directional and steerable plow (similar to a boats rudder) this might give even better performance. Adding a science instrument to the plow can make the plow even more valuable. Some instruments that could be integrated are cone penetrometers, water detecting tuned laser diodes, a drill and many others. Another area to look at it is the tradeoff between mobility methods and power. In the course of this work we started to look at this and realized a lot more work is needed.

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