Four-Wheel Rover Performance Analysis at Lunar Analog Test

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Abstract A high fidelity field test of a four-wheeled lunar micro-rover, code-named Moonraker, was conducted by the Space Robotics Lab at a lunar analog site in Hamamatsu Japan, in cooperation with Google Lunar XPRIZE Team Hakuto. For the target mission to a lunar maria region with a steep slope, slippage in loose soil is a key risk; a prediction method of the slip ratio of the system based on the angle of the slope being traversed using only on-board telemetry is highly desirable. A ground truth of Moonraker's location was measured and compared with the motor telemetry to obtain a profile of slippage during the entire four hour 500 m mission. A linear relationship between the slope angle and slip ratio was determined which can be used to predict the slip ratio when ground truth data is not available.

1 Introduction

The focus of this paper is on the soft soil traveling performance of a four-wheel skid-steer rover, code-named Moonraker - one of a dual-rover system intended for a mission to explore lunar caves by tethered-descent. Moonraker was designed specifically for travel over soft loose soil, where slippage is a primary mobility and localization concern. This section introduces Moonraker and the development background of its intended mission.

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Fig. 1 The Space Robotics Lab's dual-rover lunar rover system; the parent rover, Moonraker (left) and tethered child rover, Tetris (right).

1.1 Moonraker

Moonraker (Fig. 1) is 8 kg, and was designed to be as light as possible while not sacrificing mobility performance over lunar regolith, especially of steep slopes of 20° or more that may be encountered around cave entrances[1]. Actuation points were kept minimal, reducing mass and failure modes. The key design features are large relative wheel size and a single non-actuated catadioptric camera (implemented with a hyperbolic mirror) on the top of the rover. There is an additional TOF laser scanner in the front of the rover for detecting obstacles that the camera might fail to. These sensors can also be used to track the location of the rover and assess slippage[2].

Using four wheels, as opposed to six, allows for twice the wheel diameter, assuming the same volume constraints[1]; Larger wheel diameter reduces slip on loose soil. The use of grousers also dramatically reduces slip on loose soil, up to the point at which the grousers no longer penetrate the soil completely[4]. The wheels were therefore designed to be 20 cm in diameter with 2.25 cm grousers. Laboratory experiments indicate that a slip ratio of under 0.1 should be expected with these wheels on slopes of up to 10°.

With a single actuation axis per wheel, turning maneuvers are performed by skid steering, where the wheels on one side turn at different speeds than the other. This can take the form of a spot turn, where both sides spin in opposide directions at the same speeds, or as various degrees of course corrections where one side simply spins forward at a slower rate. Because of this maneuvering dynamic, for the purpose of calculating the total travel distance through wheel odometry, an average of each of the wheels' rotations (as measured by motor encoders) is used.

1.2 Dual Micro Rover System

The Space Robotics Lab has also developed a small, 2 kg child rover, codenamed Tetris, that together with Moonraker composes a dual rover system. Tetris will be tethered to Moonraker, which will serve as an anchor for exploration into pits and down steep cliffs. Cliff traversal experiments and Tetris mobility tests were also conducted, but are not the focus of this paper.

1.3 Team Hakuto

The Space Robotics Lab has partnered with Team Hakuto, a competitor in the Google Lunar XPRIZE (GLXP) competition. These rovers have passed space qualification tests and are intended to be launched on a lunar surface exploration mission in 2016. The field tests reported here were conducted as part of the demonstration round of the GLXP Milestone Mobility Prize, which was awarded to Team Hakuto in January 2015.

Fig. 2 Moonraker climbs a 10°slope at the Nakatajima Sand Dunes

2 Field Test

This section introduces the field test conducted at the Nakatajima Sand Dunes in Hamamatsu, Japan on December 19th, 2014. The requirements and conditions of the test as well as the equipment used are presented.

The mission was conducted over the span of 5 hours, from 11:30am until sunset at 16:30. A total travel distance of 550 m (570 m as estimated by wheel encoder odometry) was traversed. Results and performance analysis are presented in Sec. 3.

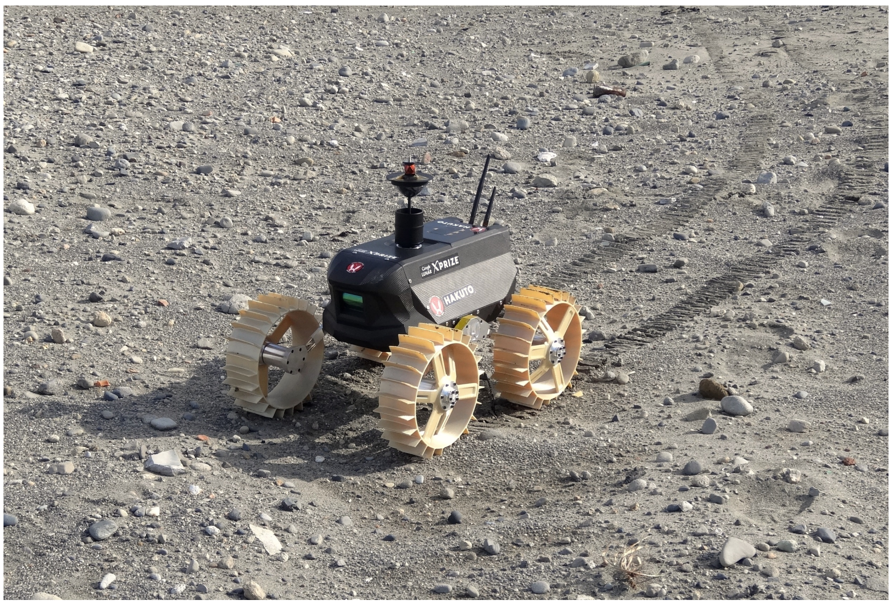

Fig. 3 Moonraker maneuvering in a rocky area. A Leica 360° prism, used for ground truth measurements, is visible on top of the mirror.

2.1 High Fidelity Requirements

In preparation for Team Hakuto's planned lunar surface mission (Sec. 1.3), the field test was conducted in "high-fidelity", or as close to the conditions of an actual lunar mission as possible. The test was set up to begin with blind deployment; the rover was placed inside the stowage envelope that will be attached to the lunar lander. After opening the envelope remotely, deploying to the surface, the test was conducted with the following requirements:

- Total travel distance of at least **500 m**

- Travel distance must be proven solely by telemetry
- No manual reset or human intervention with the hardware after deployment
- Operators forbidden to view the test site, and forbidden contact with anyone who did view the test site during the test
- A time lag of 1.3 seconds introduced on both the operator laptop and on the rover itself, in order to emulate the communication lag due to the distance between the Earth and Moon.
- Transmission data rate limited to 100 kbps in order to ensure similar bandwidth restrictions to a lunar mission.

Due to legal restrictions in Japan, a 920 MHz radio that is planned for the flight model could not be used for this field test. Instead, a 2.4 GHz 802.11 wireless module was used, dramatically reducing the range of travel from the emulated lander. This had the consequence of limiting the operation range to a 30 m radius from the emulated lander's relay radios.

2.2 Test Site

The Nakatajima Sand Dunes is a seaside region of Hamamatsu City and a protected natural environment. The key features are sprawling hills and valleys of loose sand between sections of sparse vegetation. Erosion at the borders of grassy areas create natural steep cliffs. The test site was selected to provide access to sandy slopes, rocky areas, obstacles, and a cliff.

Fig. 4 The Leica TDRA6000 Total Station tracking system used as a ground truth to the wheel odometry.

These macro-features are considered representative of the potential hazards and features of the intended lunar mission. The environment around the target skylight in lacus mortis is in a maria region, with dune-like rolling slopes, and exposed rocks in shallow craters and at the edge of the skylight. The average slope down the ramp of the skylight is expected to be an average of 15°, with unpredictable local maxima[1].

The sand itself at Nakatajima, common Earth beach sand, is not as good a match of the target environment. It is well sorted (near-homogenous) granule sizes of 0.1 mm to 1 mm, which is quite distinct from lunar regolith with very poorly sorted (heterogenous) granule sizes down to the nanometer scale. The sand is quite susceptible to slippage, however, which is sufficient for the goal of assessing relative slip performance.

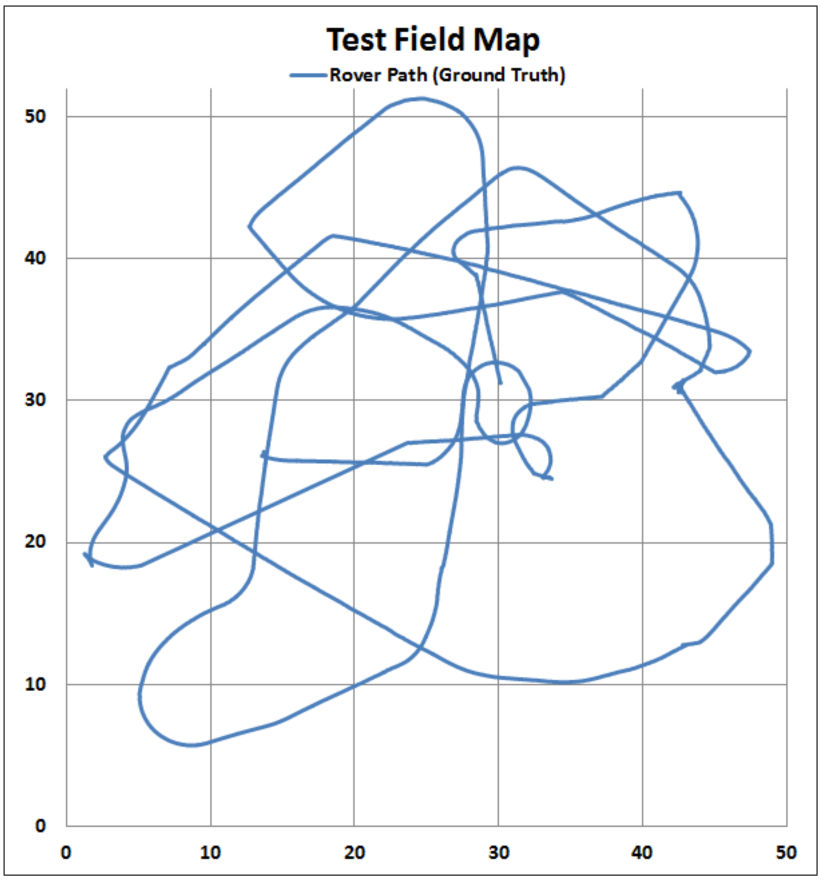

Fig. 5 Map of the rover's path around the field test site. The envelope from which the rover is deployed is at the center of the figure, coordinates (30,30)

2.3 Ground Truth Equipment

In order to evaluate the accuracy of the telemetry gathered by the rover, an external measurement of the rover's location was conducted to serve as a ground truth. A Leica Total Station surveying tool was used with a 360° prism (Fig. 3) attached to the top of the rover. The Total Station unit is equipped with a time of flight laser range finder and a pan/tilt mechanism; when used in conjunction with a reflecting prism, the target can be tracked at 7 points per second, with 3 mm accuracy. The ground truth data was used to create the map in Fig. 5 tracing the rover's movement.

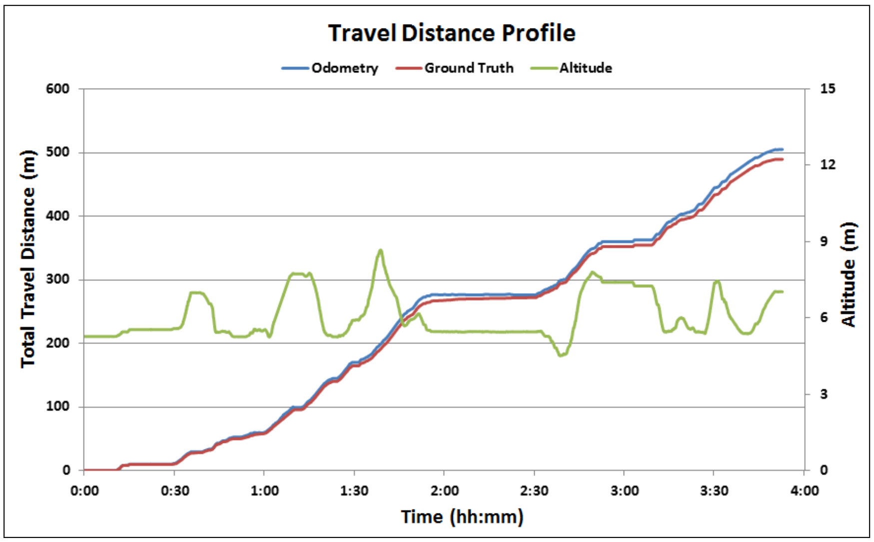

Fig. 6 The total cumulative travel distance over time, as measured by Moonraker's on-board odometry vs externally measured ground truth. Altitude is displayed to indicate the location of slopes.

3 Data Analysis

The data presented in this section corresponds to the first 500 m of the field test, over the course of 4 hours. 98% of the test was captured properly with the Total Station (Sec. 2.3), with the exception of a 5 minute gap due to a tracking error at 1 hour into the test. Fortunately no significant turns or maneuvers were made during this period of time.

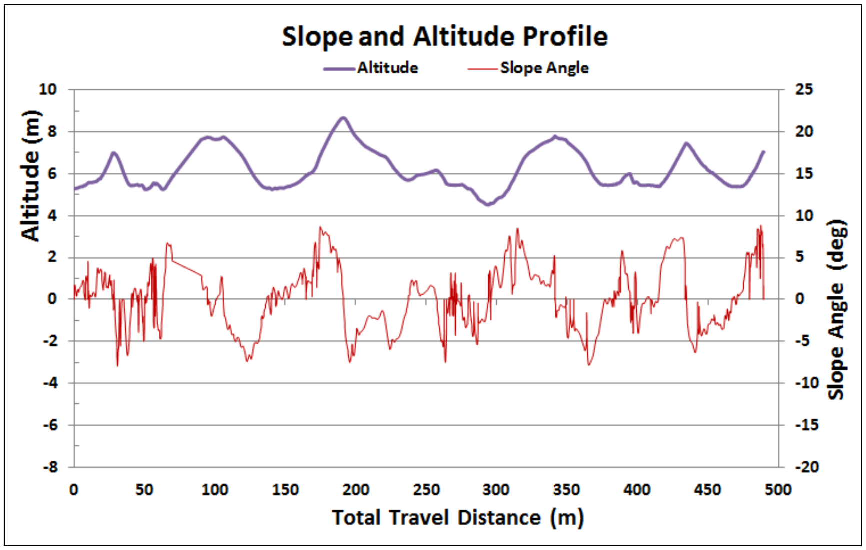

Fig. 7 The altitude of Moonraker's trajectory throughout the test is presented (above), relative to the travel distance. The slope angle at each point is also presented as the derivative of the altitude.

3.1 Travel Distance

The total distance traveled over time is shown in Fig. 6, with the altitude of the rover (above sea level) overlaid to visualize where in the test the major slopes were encountered. The slope angle profile is also presented in Fig. 7, normalized to the travel distance rather than time. The maximum average slope over two second periods never exceeded 10° for this segment of the experiment.

In Fig. 6, both the distance as estimated by the motor odometry, and the ground truth data are displayed together; their divergence over time is small but readily apparent. By the end of the ground truth data collection at the 3:50 mark, the wheel odometry-based distance estimation indicated a total 505 m distance traveled, while the ground truth measured 489.6 m.

This represents a total average slip ratio of 0.03, which is consistent with lab-based sandbox tests for the wheel configuration used (Sec. 1.1) for up to 10° slope environments. However due to the uneven and randomly undulating terrain, a total average value does not provide enough data to accurately determine the rover's total travel distance at any given time. It is useful to know what the slip ratio profile is throughout the mission, ideally in real time using only rover telemetry[3].

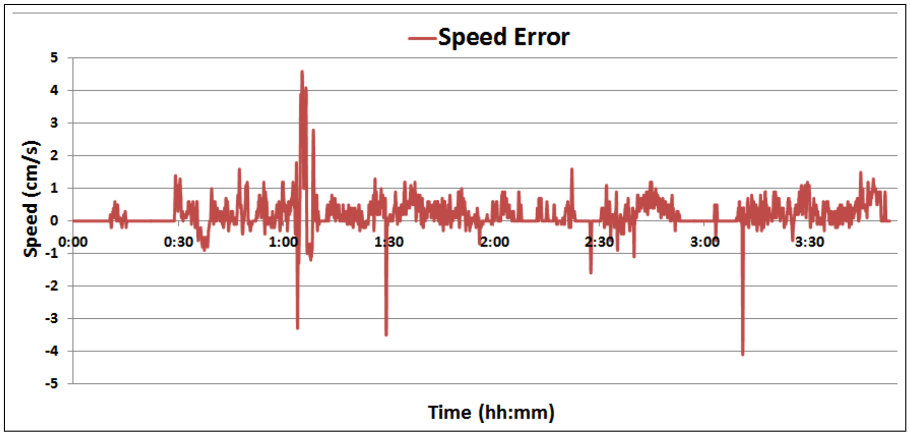

Fig. 8 This graph displays the difference between the speed as calculated by the wheel odometry and by ground truth, which indicates slippage.

3.2 Slip Ratio

The speed of Moonraker at each moment, both as estimated by averaging each wheels' encoder odometry and through ground truth, can be used to determine the slip. Fig. 8 displays the error of the odometry estimation as a simple difference. These speed data were used to calculate the slip ratio of the rover as a whole every two seconds according to the following formula (ignoring 0 and near-zero wheel speed values):

$$1 - (rover\ speed/wheel\ speed) \tag{1}$$

where *rover speed* is the ground truth data and *wheel speed* refers to the speed of the rover as estimated by averaging the encoder odometry from all four wheels. This result was then median filtered to remove outliers. Fig. 9 shows the slip ratio as clusters of data points along the timeline of the field test. The resulting slip ratios occasionally vary widely, but also cleanly cluster together. The slope angles from Fig. 7 are included for comparison; as expected, the slip ratios have a clear relationship with the corresponding slope angle.

3.3 Slope Angle-Slip Ratio Relationship

The relationship between the slip ratio and the slope angel is presented in Fig. 10, where each of the 6800 slip ratio data points is plotted according to the angle of the slope at the time the measurement was taken. The majority of points are clustered neatly between 0 and 0.2 slip ratio. There are many data points outside of any pattern and artifacts that follow unpredictable trajectories across the graph. Some of these

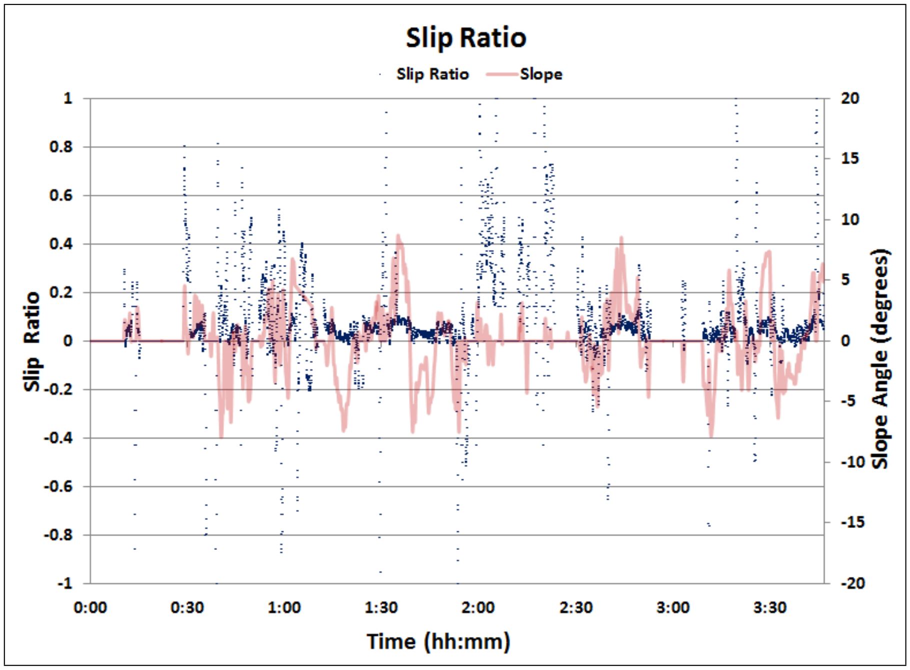

Fig. 9 The slip ratio is calculated every 2 seconds throughout the field test, and is displayed here in conjunction with the corresponding slope angle. The data points cluster around strong clear slippage events.

appear to be due to lateral slip (which is unaccounted for in this study), while others are due to transient-state slip ratios during turning maneuvers.

Fig. 11 shows a linear regression calculated after data from turning maneuvers with negligible forward movement (eg 2:00-2:30 in Fig. 6) are removed. The linear regression equation is as follows:

$$y = 0.0066x + 0.0426 \tag{2}$$

The correlation coefficient is 0.1122, with a standard deviation of 0.03. This is a loose, but significant linear trend from near-zero to slight negative slip (slipping forward) on downward slopes of 9°to 0.1 slip ratio at 9°upward slope. This linear trendline can therefore be used to estimate the slip ratio of the rover at any given time using only an IMU to determine the angle of the slope that the rover is traversing, even before accounting for the rover's heading with respect to the slope being traversed.

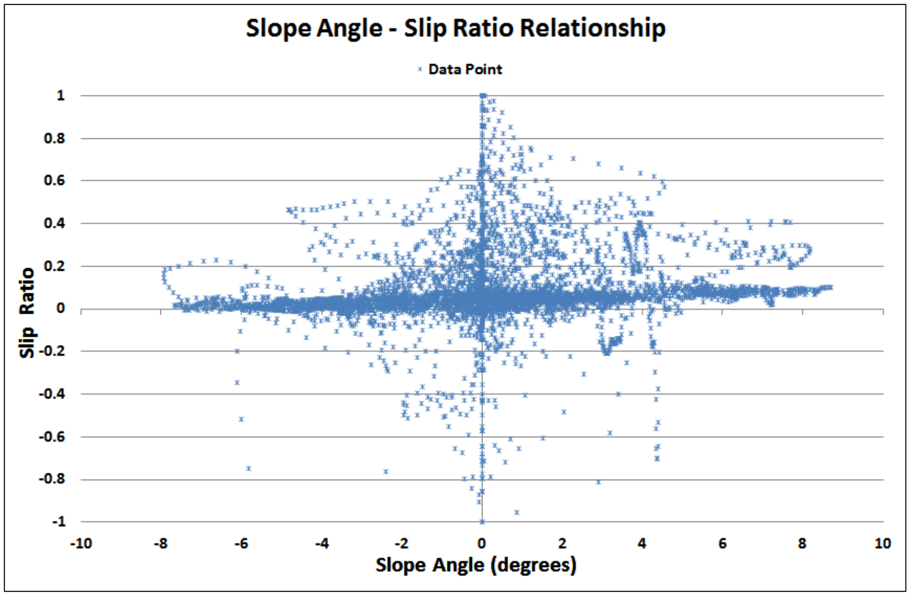

Fig. 10 A cloud of slip ratio data points relative to the angle of the slope they were measured at. Each point represents a 2 second period of time. Fig. 11 shows a magnified view.

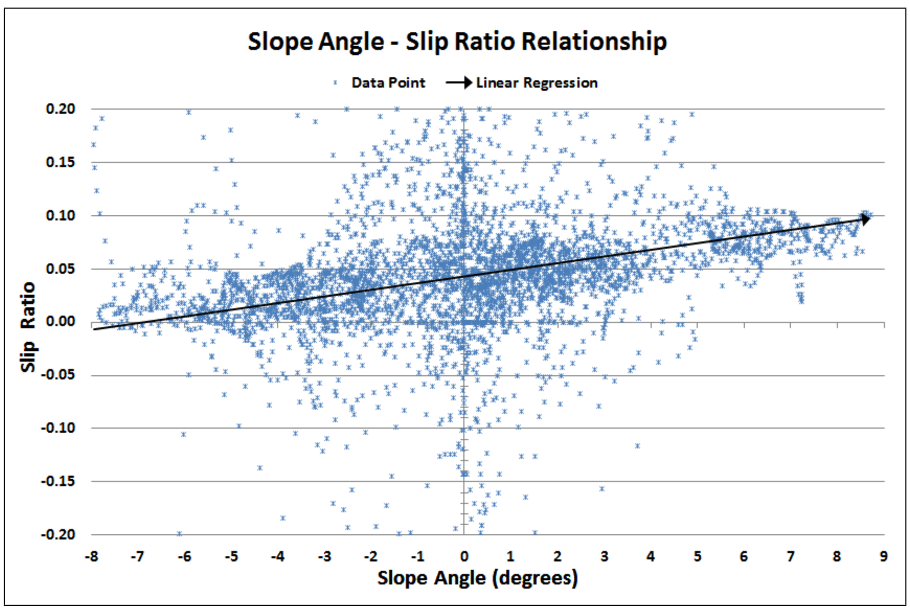

Fig. 11 A magnified view of Fig. 10; a linear trendline from 0 to 0.1 slip ratio is indicated.

4 Conclusion

Slippage is a very important threat to wheeled mobility, which needs to be understood and accounted for in rover missions to the lunar mare and similar environments on Mars[3]. Controlled laboratory tests are useful for validating the relative effectiveness of different mobility configurations, but field validation is necessary for determining the actual performance in a real environment. At our field test in a lunar analog environment, we traveled over 500 m, and measured a high precision ground truth in order to perform a moment-by-moment slip analysis.

Our results indicate a linear relationship between the angle of the slope being traversed at any given time and the slippage occurring. This linear relationship gives valuable insight into the extent of slippage that can be expected based on a simple easily measurable characteristic of the rover's environment - slope angle, without concern to the heading of the rover with respect to the slope. The data used in this investigation, having come from a high fidelity field test at a lunar analogue environment, gives us high confidence that this linear relationship can be a useful component of navigation systems implemented for lunar and martian wheeled rover systems.

4.1 Future Work

This information can be used in navigation systems to correct rovers wheel odometry in real time. By extracting the heading of the rover from the camera data, a system to account for lateral slopes/slip would further improve the accuracy of wheel odometry for navigation systems. There is also room to investigate refining or defining this linear relationship for different soils without the use of ground truth equipment.

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